Opportunity Report

"Towards Enhanced EU-US ICT Pre-competitive Collaboration"

Internet of Things / Cyber-physical Systems

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Executive Summary

This report describes the major results that were obtained by the PICASSO Expert Group on the Internet of Things (IoT) and cyber-physical systems (CPS) in the PICASSO project.

The major contributions of this report are:

- **Technology themes** (chapter 3) and **collaboration opportunities and mechanisms** (section 4.3) that have been identified as being promising for EU-US collaboration, synthesized based on comprehensive analyses of:
- The **EU and US research and innovation priorities** in the technology sectors and related application domains (chapter 2),
- The **EU-US funding and collaboration landscape** (section 4.1), and
- **Barriers for EU-US collaboration** (section 4.2).

In chapter 3 of this report, the PICASSO Expert Group on IoT/CPS (www.picasso-project.eu/iotcps-expert-group) has defined technology themes that are promising for EU-US collaboration:

- Closing the Loop in IoT-enabled Cyber-physical Systems
- Model-based Systems Engineering
- Trust, (Cyber-)security, Robustness, Resilience, and Safety
- Integration, Interoperability, Flexibility, and Reconfiguration
- Autonomy and Humans in the Loop
- Situational Awareness, Diagnostics, and Prognostics

Collaboration opportunities and mechanisms are defined in section 4.3 of this report. The IoT/CPS Expert Group has found that lightweight collaboration measures currently have the best chance of success, and that the EC should aim for the establishment of such measures with both, federal US agencies and US industry and industry-led associations. Measures should aim to establish roadmaps and benefit assessment for EU-US collaboration, the set-up of suitable matchmaking initatives, and lightweight joint research and innovation with agencies and industry.

This report is mainly addressed to academic and industrial experts, academic institutions, companies and industry-led associations, and policy makers willing to enhance trans-Atlantic collaboration by building on top of common IoT/CPS opportunities, needs, and challenges, both technological and societal.

The contents of this report are based on in-depth discussions with a large network of international experts, analytical research by the Expert Group, preliminary PICASSO results (i.e. the reports (1), (2), and (3)) and other feedback collection mechanisms such as a public consultation on the PICASSO website.

The IoT/CPS opportunity report was circulated widely for feedback collection to leading individual researchers and practitioners in the EU and the US, to the expert networks of the projects and initiatives *AIOTI*, *CPS Summit*, *BILAT USA 4.0*, *TAMS4CPS*, *CPSoS*, *Road2CPS*, *oCPS*, and *CPSE Labs*, and to the industry associations *ARTEMIS-IA*, *Industrial Internet Consortium* (*IIC*), and *SafeTRANS*. Furthermore, the report contents were presented and discussed in detail with an international audience in an interactive webinar that was held by the PICASSO IoT/CPS Expert Group on February 2, 2017[1], and in-depth 30-minute personal interviews were subsequently conducted with senior representatives from the US government agencies *NSF* (*National Science Foundation*) and *NIST* (*National Institute of Standards and Technology*), the IoT and CPS units of the European Commission, the *ERA-*

[1] More information and a summary is available at: http://www.picasso-project.eu/newsevents/project-events/iot-cps-webinar-feb2017.

NET instrument, the industry-led associations *Industrial Internet Consortium* (*IIC*), *Smart Manufacturing Leadership Coalition* (*SMLC*), and *ARTEMIS-IA*, the *University of California*, the *Intelligent Manufacturing Systems* (*IMS*) global research and business innovation program, and the *National Council of University Research Administrators* (*NCURA Global*).

Since its previous revision V1.0.1 that was published on March 19, 2017, the report has been updated to reflect the results of the activities of the IoT/CPS Expert Group since then. In particular, the following sections were updated:

- Minor updates and corrections were made in all of the subsections of chapter 2 to reflect the results of EG-internal discussions of the report.
- The technology themes defined in chapter 3 were prioritized in discussions within the EG and with external stakeholders, and this prioritization has been added below. **Autonomy and Humans in the Loop** currently has the highest priority and should be in the focus on EU-US collaboration. Two other themes are currently of high importance as well according to our discussions, **Model-based Systems Engineering** and **Trust and Cyber Security**.
- The description of the barriers to EU-US collaboration in section 4.2 was updated to reflect internal EG discussion results.
- The concrete collaboration opportunities in section 4.3 were refined and revised based on the results of the activities of the EG since the publication of the previous version of this report.

The strategic initiative proposals that are described in the PICASSO report D3.2 were developed based on the insights and investigations described in the opportunity report. Thus, the opportunity report provides a common view on priorities and future cooperation opportunities between the EU and the US and is a strong basis and guideline for concrete EU-US collaboration actions of the PICASSO project.

The PICASSO Project

The aim of the 30-months PICASSO project is (1) to reinforce EU-US collaboration in ICT research and innovation focusing on the pre-competitive research in key enabling technologies related to societal challenges - 5G Networks, Big Data, Internet of Things and Cyber Physical Systems, and (2) to support the EU-US ICT policy dialogue by contributions related to e.g. privacy, security, internet governance, interoperability, ethics.

PICASSO is oriented to industrial needs, provides a forum for ICT communities and involves 24 EU and US prominent specialists in the three technology-oriented ICT Expert Groups - 5G, Big Data, and IoT/CPS - and an ICT Policy Expert Group, working closely together to identify policy gaps in the technology domains and to take measures to stimulate the policy dialogue in these areas. A synergy between experts in ICT policies and in ICT technologies is a unique feature of PICASSO.

A number of analyses will be accomplished, as well as related publications, that will for a major part be made public and contribute to the project's outreach. Dedicated communication and dissemination material will be prepared that should support the operational work and widespread dissemination though different channels (website, social media, publications …). The outreach campaign will also include 30+ events, success stories, factsheets, info sessions, and webinars.

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About the PICASSO Project:

PICASSO is co-funded by the European Commission under the Horizon 2020 programme.
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Duration: 30 months
Total budget: 1,160,031 €, including a contribution from the European Commission of 999,719 €
Project Website: http://www.picasso-project.eu/

PICASSO Consortium Members:

inno	**inno TSD, France** – one of Europe's leading innovation management consultancy firms, specialised in helping major private and public stakeholders design and implement R&D and innovation projects. https://www.inno-tsd.fr/en
tu technische universität dortmund	**TECHNISCHE UNIVERSITÄT DORTMUND, Germany** – a leading German technically oriented research university with strong research groups in big data, communications, smart grids, e-mobility and cyber-physical systems. http://www.tu-dortmund.de
THHINK WIRELESS TECHNOLOGIES LTD	**THHINK WIRELESS TECHNOLOGIES LIMITED, United Kingdom** - an ICT company founded in 2009 after more than a decade of research and development in wireless and energy harvesting technologies. http://www.thhink.com/
ATC ATHENS TECHNOLOGY CENTER	**ATC SA, Greece** - an SME and Technology Centre in the field of ICT participating in 3 ICT European Technology Platforms: NESSI (Steering Committee member), NEM (member) and NETWORLD2020 (member), and founding member of European Big Data Value Association. http://www.atc.gr

APRE Agency for the Promotion of European Research	**AGENZIA PER LA PROMOZIONE DELLA RICERCA EUROPEA, Italy** – a non-profit research organisation, grouping together more than 100 members, including public and private research centres, industries, industrial associations, chambers of commerce, science parks and more than 50 universities, with the main objective to promote the participation in national and European RTD programmes. http://www.apre.it/
Honeywell	**HONEYWELL INTERNATIONAL INC, United States** – a multinational company and global leader that invents and manufactures technologies to address some of the world's toughest challenges initiated by revolutionary macrotrends in science, technology and society. The company's products and solutions are focused on energy and the environment, safety and security, and efficiency and productivity. http://honeywell.com/
GNKS Consult	**GNKS CONSULT BV, Netherlands** - conducting strategic and policy research and evaluation, building on excellence in understanding of the impact of the emerging Global Networked Knowledge Society http://www.gnksconsult.com/
TECHNISCHE UNIVERSITÄT DRESDEN	**TECHNISCHE UNIVERSITÄT DRESDEN, Germany** - a full-scale university with 14 faculties, covering a wide range of fields in science and engineering, humanities, social sciences and medicine. https://tu-dresden.de/
FIU FLORIDA INTERNATIONAL UNIVERSITY	**FLORIDA INTERNATIONAL UNIVERSITY, United States** - The Miami-Florida Jean Monnet Center of Excellence, (MFJMCE), a member of the global network of EU-sponsored Jean Monnet centers, has the mission to promote teaching, research and outreach activities relating to the EU. http://www.fiu.edu/; https://miamieuc.fiu.edu/
Technological Leadership Institute	**UNIVERSITY OF MINNESOTA, United States** – The Technological Leadership Institute bridges the gap between business and engineering. TLI's mission is to develop local and global leaders for technology enterprises. https://tli.umn.edu/

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List of Acronyms

3GPP	3rd Generation Partnership Program
4G	4^{th} Generation
5G	5^{th} Generation
AI	Artificial Intelligence
AIOTI	Alliance of IoT Innovation
AV	Autonomous Vehicle
AWS	Amazon Web Services
B2B	Business-to-business
B2C	Business-to-customer
BBI	Bio-based Industries
BD	Big Data
BDVA	Big Data Value Association
BDVPPP	Big Data Value Public Private Partnership
CEDR	Conference of European Directors of Roads
CERN	Conseil Européen pour la Recherche Nucléaire
CPS	Cyber-physical System
CPSoS	Cyber-physical System of Systems
CPS-VO	CPS Virtual Organization
CPU	Central Processing Unit
CS	Clean Sky
CSAAC	Cyber Situational Awareness Analytical Capabilities
D2D	Device-to-Device
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DISA	Defense Information Systems Agency
DoC	Department of Commerce
DoD	Department of Defense
DoDIN	DoD Information Networks
DoE	Department of Energy
DoS	Department of State
DoT	Department of Transportation
DSL	Digital Subscriber Line
DSM	Digital Single Market
EC	European Commission
ECSEL	Electronic Components and Systems for European Leadership
EeB	Energy-efficient Buildings
EG	Expert Group
EPI	European Platform Initiative
ERA	European Research Area
EU	European Union
FBMC	Filter-Bank Multi-Carrier
FCC	Federal Communications Commission
FCH	Fuel Cells and Hydrogen
FET	Future and Emerging Technologies
FIRE	Future Internet Research & Experimentation
FoF	Factories of the Future
FP7	Framework Programme 7

FY	Financial Year
Gbps	Gigabit per second
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GENI	Global Environment for Networking Innovations
GFDM	Generalized Frequency-Division Multiplexing
GHz	Gigahertz
H2020	Horizon 2020
H2M	Human-to-machine
HD	High-definition
HMI	Human Machine Interface
HPC	High Performance Computing
HPUE	High Performance User Equipment
IA	Industry Association
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IERC	IoT European Research Cluster
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IM	Innovative Medicine
IMS	Intelligent Manufacturing Systems
INCOSE	International Council on Systems Engineering
IoT	Internet of Things
IP	Intellectual Property
IPR	Intellectual Property Rights
ISM	Industrial, Scientific, Medical
ITER	International Thermonuclear Experimental Reactor
ITS	Intelligent Traffic System
ITU	International Telecommunication Union
JTI	Joint Technology Initiative
JU	Joint Undertaking
LTE	Long Term Evolution
M2M	Machine-to-Machine
M&S	Modeling and Simulation
MEC	Mobile Edge Computing
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MoU	Memorandum of Understanding
ms	Millisecond
NACFAM	National Coalition for Advanced Manufacturing
NB-IoT	Narrowband IoT
NCP	National Contact Point
NCURA	National Council of University Research Administrators
NFV	Network Function Virtualization
NGI	Next Generation Internet
NGMN	Next Generation Mobile Networks
NIH	National Institutes of Health
NIPRNet	Nonsecure Internet Protocol Router Network
NISD	Network and Information Security Directive

NIST	National Institute of Standards and Technology
NIT	Networking and Information Technology
NITRD	Networking and Information Technology Research and Development
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
OCF	Open Connectivity Foundation
OFDM	Orthogonal Frequency Division Multiplexing
OMG	Object Management Group
PAWR	Platforms for Advanced Wireless Research
PCAST	President's Council of Advisors on Science and Technology
PPP	Public Private Partnership
PWG	Public Working Group
QoE	Quality of Experience
R&D	Research and Development
R&I	Research and Innovation
RAT	Radio Access Technology
RDI	Research, Development, Innovation
RFC	Request for Comments
SAE	Society of Automotive Engineers
SDAV	Scalable Data Management, Analysis and Visualization
SDN	Software Defined Networking
SEED	Standard Energy Efficiency Data
SIPRNet	Secret Internet Protocol Router Network
SME	Small and Medium-sized Enterprises
SMLC	Smart Manufacturing Leadership Coalition
SoS	System of Systems
SOTA	State of the Art
SPIRE	Sustainable Process Industry
SRA	Strategic Research Agenda
SSG	Senior Steering Group
Tbit	Terabit
Tbps	Terabit per Second
TRL	Technology Readiness Level
TTIP	Transatlantic Trade and Investment Partnership
TV	Television
UE	User Equipment
UHD	Ultra High Definition
URLLC	Ultra-reliable Low-latency Communications
US	United States
USGS	US Geological Survey
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
V5GTF	Verizon 5G Technology Forum
VDA	Verband Der Automobilindustrie
VPN	Virtual Private Network
ZT-OFDM	Zero-tail OFDM

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1. Introduction

Over the last years, different definitions of the Internet of Things (IoT) have been created that describe the IoT as both a technological system and a concept. For example, in (4), the IoT is defined as "a new era of ubiquitous connectivity and intelligence, where a set of components, products, services and platforms connects, virtualizes, and integrates everything in a communication network for digital processing." while the IERC definition[2] states that the IoT is "a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network.".

Within PICASSO, we focus less on the connectivity aspect of the IoT, which has received major attention over the last years and has led to mature solutions for IoT-connected devices, and more on the opportunities that the provision of streams of real-time data from a large number of IoT-connected devices with sensing capabilities provides for monitoring, optimization, management, and intelligent service provision in modern large-scale technical systems. In such technical systems, which are often called *cyber-physical systems* (*CPS*), real-time computing elements and physical systems interact tightly. Cyber-physical systems are ubiquitous, as computing devices and software are enabling and enhancing the performance of all except the simplest technical systems. The most challenging class of cyber-physical systems are cyber-physical systems of systems (CPSoS[3]) that are characterized by being spatially distributed, having distributed control, supervision, and management with partial autonomy of the subsystems, are dynamically reconfigured on different time scales, can show emerging behaviors, and involve human interactions (e.g. with operators or managers). Examples of cyber-physical systems of systems are the electrical grid, railway systems, the public transport system of a city, smart buildings, and production processes with many cooperating elements such as robots, machines, warehouses, or large processing plants with many process units.

CPS and CPSoS are equipped with a large number of sensing devices. The IoT will make the access to the information provided by these sensors a lot simpler and more flexible, and the connectivity provided by the Internet of Things will become an enabling technology for cyber-physical systems of systems in which the loop from a myriad of sensors to the way the systems are operated and also to the demands of the users is closed (5). This will enable improved monitoring, management, and hence new levels of energy and resource efficiency, product and service quality, and safe and reliable operation. According to the PICASSO definition, the IoT is seen as an enabling technology for CPS or CPSoS, while other, more encompassing definitions include also applications outside the domain of CPS and CPSoS, such as IoT-connected home entertainment systems or geolocation-enabled tracking infrastructures for consumer items.

The merging of IoT and CPS into closed-loop, real-time *IoT-enabled cyber-physical systems* is seen as an important future challenge. As examples, the international industry-led association *Industrial Internet Consortium* (*IIC*) promotes that "Companies need to close the loop across associated processes." (6), and our personal interview contacts agree that closing the loop via the IoT is one of the major challenges and opportunities in the CPS and IoT domains. In the EU, this challenge is recognized by several institutions, such as *the ARTEMIS Industry Association* who e.g. believe that the "Internet of Things, and consequently the Things of the Internet, and Cyber-Physical Systems are complementary directions which together will help to shape a society where humans and machines increasingly interact to provide services and solutions for the benefit of society that are inconceivable with the present state-of-the-art technology" (7), and the *European Alliance of IoT Innovation* (*AIOTI*) who see this as a macro-challenge, stating "Getting billions of objects duly connected and managing these to create a

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[2] See http://www.internet-of-things-research.eu/about_iot.htm

[3] See e.g. www.cpsos.eu

reliable monitoring/actuating substrate only partially caters for the challenges ahead. These challenges cannot be complete without considering how to handle the huge amount of data produced and how to transform it into useful and actionable knowledge." (8). On the US side, for example the US branch of Samsung sees the CPS draft framework by NIST as an important prerequisite for the future of the IoT (9), and the NSF has recently initiated a successful IoT focus initiative within its CPS section and is currently funding several research projects that cover the idea of using the IoT as an enabler for CPS.

The enormous potential of novel CPS and IoT technologies has been recognized by both the EU and the US. The social and economic challenges are common across the world, and there are opportunities for the EU and the US to work together on these global challenges for mutual benefit, not only in allowing solutions from EU and US providers to be sold within each other's economic areas but also on a world-wide scale (2). In addition to economic benefits, there will be benefits to society and to end-users. Joint research and innovation will lead to a faster development of better solutions and will enable societal challenges to be addressed more efficiently.

The objective of the PICASSO Expert Group on IoT/CPS was to identify the key societal challenges where these technologies will offer a large potential for improvements, to analyze technology strengths and technology gaps in the EU and in the US, and to make proposals for future EU-US collaboration topics on IoT-driven cyber-physical systems, in particular on how to handle the huge amounts of real-time data produced by IoT-connected sensors and how to transform it into useful knowledge and actions that will improve the performance, cost-efficiency, and safety of cyber-physical systems.

The objective of the IoT/CPS-related parts of this report is to provide a selection of EU-US cooperation opportunities on IoT/CPS that were identified within the PICASSO project. The contents were compiled based on several sources. The most important inputs were derived from discussions with the PICASSO Expert Group on IoT/CPS[4] and from personal interviews with external experts that provided valuable insights into the R&I landscapes, needs, gaps, and opportunities on both sides of the pond. This input was enriched with background information from other sources that include e.g. the PICASSO reports (2), (1), and (3), technological and strategic documents and roadmaps that were published by relevant EU and US initiatives and institutions, and a database of R&I projects on the topics of IoT and CPS that are currently funded in the EU and the US.

The contents of the IoT/CPS sections of this report were widely distributed and were validated and refined via different feedback collection efforts. In January 2017, a draft version of the IoT/CPS opportunity report was circulated for questionnaire-based feedback collection, including to leading individual researchers and practitioners in the EU and the US and to the expert networks of the projects and initiatives *AIOTI*, *CPS Summit*, *BILAT USA 4.0*, *TAMS4CPS*, *CPSoS*, *Road2CPS*, *oCPS*, and *CPSE Labs*[5]. Particular focus was given to industrial distribution by the involvement of the industry associations *ARTEMIS-IA*, *Industrial Internet Consortium* (*IIC*), and *SafeTRANS*[6]. In addition, the report contents were presented and discussed with an international audience in an interactive webinar that was held by the PICASSO IoT/CPS Expert Group on February 2, 2017[7], and the report was published on the PICASSO website for public consultation.

Based on a revised version of the IoT/CPS section of the report, in-depth personal interviews (of appr. 30 minutes length each) were subsequently conducted with senior representatives from the US government agencies *NSF* (*National Science Foundation*) and *NIST* (*National Institute of Standards and Technology*), the IoT and CPS units of the European Commission, the *ERA-NET* instrument, the industry-led associations *Industrial Internet*

[4] See http://www.picasso-project.eu/iotcps-expert-group

[5] http://www.aioti.org; http://cps-vo.org/group/cps-summit; http://www.euussciencetechnology.eu; http://www.tams4cps.eu; www.cpsos.eu; www.road2cps.eu; http://ocps.ele.tue.nl; www.cpse-labs.eu

[6] https://artemis-ia.eu; http://www.iiconsortium.org; http://www.safetrans-de.org

[7] More information and a summary is available at: http://www.picasso-project.eu/newsevents/project-events/iot-cps-webinar-feb2017.

Consortium (*IIC*), *Smart Manufacturing Leadership Coalition* (*SMLC*)[8], and *ARTEMIS-IA*, the *University of California*, the *Intelligent Manufacturing Systems* (*IMS*) global research and business innovation program, and the *National Council of University Research Administrators* (*NCURA Global*), the only US-based H2020 *National Contact Point* (*NCP*). These interviews resulted in valuable governmental, academic, and industrial feedback on the technological contents of the report and were used as a basis for the design of the concrete collaboration opportunities and mechanisms for the IoT and CPS domains. Further, the topics were discussed at the First Transatlantic Symposium on ICT Technology and Policy in Minneapolis in June 2017, and refined. Additional feedback was obtained throughout June 2017-May 2018.

[8] https://smartmanufacturingcoalition.org

2. Research and Innovation Priorities in the EU and the US

This section summarizes the technological research and innovation priorities in the EU and the US in the sectors of the Internet of Things (IoT) and of cyber-physical systems (CPS), and the needs and drivers for important application sectors, including smart cities, smart energy, smart transportation, and smart production.

The section is based on several sources, both from within PICASSO and beyond. In addition to inputs by the PICASSO Expert Group on IoT/CPS and from external experts obtained during our feedback collection efforts with funding agencies, industry, and academia, relevant documents and roadmaps by different strategic initiatives and institutions were analyzed (a graphical overview is given in Figure 1, more details are provided in the subsections below). Many of these documents were developed in year-long efforts by large networks of experts, and if a topic appears in several, or even all, of these documents, it is reasonable to assume that it is seen a high-priority topic. The suitability and correctness of the identified R&I priorities was confirmed during the feedback collection process of the IoT/CPS Expert Group in early 2017 in which funding agency representatives and other experts agreed that the chosen priorities have top priority in the EU and the US.

In addition, several PICASSO reports served as sources. The PICASSO report "Panorama of the ICT landscape in the EU and US" (2) provides a comprehensive overview of the current ICT landscape (including networks, initiatives, policies, and regulations) in the EU and US. Its focus lies on the application sectors of smart cities, smart energy, and smart transportation, but it also gives an overview of the IoT and CPS domains. The PICASSO report "Analysis of Industrial Drivers and Societal Needs" (1) provides an analysis of EU-US industrial drivers and societal needs and barriers for different application and technology domains, which were validated in a major effort via the interviewing and feedback collection from 150 experts from different industrial domains. This report has provided valuable pointers, and it was particularly useful for clarifying the impact that novel technological developments will have on application domains. The summary of the drivers and needs of application domains is partly based on this report.

To get a feel for the R&I funding priorities in the EU and US, and as an input for the PICASSO ICT toolkit *CROSSROADS*, a database of IoT and CPS R&I projects was created that covers the projects currently being funded by the most important funding programmes and agencies, including FP7, H2020, and EUREKA/ITEA on the EU side and the NSF, NIST, and the DoE on the US side. This database was used to identify focus areas that are currently getting funded in the EU and the US[9].

This section is structured as follows: Section 2.1 briefly summarizes the major societal cross-domain challenges in the EU and the US that drive the introduction of novel IoT/CPS technologies. Section 2.2 describes technological developments in the EU and the US that are important enabling technologies for IoT-enabled CPS, but that are not the focus of the R&I priorities that are relevant for PICASSO. Section 2.3 provides a list of R&I priorities for cyber-physical systems that are in the focus of EU and US research and innovation efforts, and section 2.4 does the same for the Internet of Things. Section 2.5 summarizes the major needs and drivers in important application sectors, and section 2.6 closes this part of the report with an analysis and comparison of EU and US research and innovation priorities, based on the previous sections and on expert inputs that were obtained during feedback collection and personal interviews by the IoT/CPS Expert Group with funding agencies, industry associations, and individual researchers and practitioners.

[9] The database does not cover all R&I funding in the EU and the US, which amounts to several hundred projects overall (including more than 300 funded by the NSF on CPS topics alone). To reduce the number of projects to be analyzed, only the projects with the largest financial funding were considered, and only those projects were included that are relevant to the focus of this report, i.e. IoT-enabled CPS. Overall, the database consists of 68 projects on CPS topics and 55 projects on IoT topics.

Figure 1: Documents by these strategic initiatives and institutions were used to create the IoT/CPS R&I priority lists.

2.1. Cross-domain Drivers and Needs

This section briefly summarizes the major overarching societal challenges that are currently seen as the major drivers for the development and deployment of novel IoT/CPS-based technologies in the EU and the US. It is based on the PICASSO reports (2) and (1) and on discussions with the IoT/CPS Expert Group members and was validated during the feedback collection process.

Advancing climate and environmental sciences for sustainability, and the provision of clean, efficient energy are seen as major societal drivers in the EU and the US. In this area, there is major demand by customers and governments, and companies see a large opportunity and are seeking to satisfy needs with both products and services.

Globalization and increased urbanization are seen as a key challenge for the future. The predicted growth of the world population, which is estimated to reach 9 billion by 2050, the move towards cities and mega-districts, and the expected deepening of international integration and globalization will create large challenges to provide energy supply, logistics, health care, security, food, and water. Smart ICT will be crucial for providing interconnectivity, information, and optimization of services to solve these challenges.

Increases in connectivity and autonomy in all domains and the advent of smart and connected devices will drive technology and will provide numerous opportunities for the development of smart ICT solutions for the solution of societal challenges, such as the decarbonization of cities, the grid, production, and transport, or the introduction of renewable energy sources.

Vulnerability, trust and trustworthiness, privacy, (cyber-)security, and safety are crucial drivers that are gaining relevance in all practical domains, particularly in the US.

The **Industrial Internet of Things** is seen as a major driver for the next generation of industrial systems and infrastructures.

2.2. Enabling Technologies

Future IoT-enabled cyber-physical systems will be based on advances in a number of enabling technologies, many of which are currently in the focus of research and innovation programmes and efforts in the EU and US. This section briefly summarizes those enabling technologies that are of the highest importance to IoT-enabled CPS. It is based on the roadmaps and strategic documents that are described in subsequent sections, on the PICASSO reports (2) and (1), on discussions with the IoT/CPS Expert Group members, and on inputs obtained in personal interviews and at the IoT/CPS webinar that was held on Feb. 2, 2017, and the contents were validated during the feedback collection process.

The advancement of **information technology and high-performance computing** is a major focus in both the EU and the US. In this area, major topics include the development of cloud, edge, and fog computing technologies, ubiquitous mobile computing, distributed and heterogeneous systems, novel technologies for data and signal processing, and more generally advances in software engineering and algorithms.

Another area that is currently in the focus of intense R&I efforts is **communication and network technology**, reflecting the enormous growth in connectivity. Here, the current focus is on topics such as reliability and security in communication systems, real-time-capable communication, open and scalable communication and networking architectures, machine-to-machine (M2M) communications, network management and discovery, and broadband wireless and 5G communications (also refer to the 5G sections of this report).

The current trend towards "being always connected" and the need to **connect and power many billions of IoT-enabled devices** poses major challenges that go beyond traditional networking and communication technologies (8). These include the need for ubiquitous connectivity schemes that support the syntactic and semantic integration of heterogeneous IoT sub-systems, mechanisms to provide reliable electricity to power many billions of IoT devices, such as energy harvesting technologies to power autonomous edge devices, scalable registration and discovery of IoT devices/services, bandwidth provision and management for connecting tens of billions of devices, and M2M communication optimization.

The need for highly reliable real-time IoT applications is driving major R&I initiatives and efforts to develop and mature the **Tactile Internet** that will enable low-latency communications in combination with high availability, reliability, and security. Some important topics in this area, which is covered within PICASSO by the 5G Expert Group, are the detection of security threats and anomalies in wireless communications, the orchestration of resources for reliability and dependability, and the virtualization of IoT functions (8).

The ubiquitous access to information via the IoT will also require advances in **pervasive sensing and sensor technologies**. Here, major topics are making sensors less expensive and more affordable, in-memory computing power of sensing devices, increasing the speed of data exchange between sensors and the internet, and the virtualization of sensing.

Major advances are currently also made in the areas of **data processing** and **data analytics**, which are covered in PICASSO by the Big Data Expert Group (also refer to the Big Data section of this report).

2.3. Cyber-physical Systems (CPS)

CPS are one of the key pillars of the European *Digital Single Market Strategy* and the *Digitising European Industry* initiative, the innovation programme *Smart Anything Everywhere*, and other major European initiatives, such as *H2020*, *EUREKA/ITEA*, the *ECSEL Joint Undertaking*, and the *ARTEMIS Industry Association*, the latter two funding large-scale lighthouse projects that are essential to creating CPS reference technology platforms and open interoperability standards, such as *CRYSTAL*, *CESAR*, and *EMC2*. In addition, a large number of smaller CPS-related R&I projects are funded in different EU programmes, where the EC strategy has been to combine these into clusters, e.g. on CPS and on SoS (systems of systems). The EU-level initiatives are complemented by national programmes, such as *Industrie 4.0* in Germany that drives work on CPS in manufacturing, or the Austrian programme *Produktion der Zukunft*. In addition, CPS competence centres have been set up to engage with European SMEs, and several public-private partnerships (PPPs) have been started that are related to CPS or enabling technologies, such as *Factories of the Future* (*FoF*), *Cybersecurity*, *5G*, *Future Internet*, and *Robotics*.

In the US, the CPS *Senior Steering Group* (*SSG*) of the *Networking and Information Technology Research and Development* (*NITRD*) Program is responsible for coordinating programmes, budgets, and policy recommendations for CPS research and development, and CPS-related basic research is mainly being driven by the NSF Cyber-Physical Systems programme that has funded over 350 projects that focus on fundamental CPS research, which has for example led to the creation of a thriving *CPS Virtual Organization* (*CPS-VO*). Other federal agencies have independent, often more applications-oriented research efforts. For example, DARPA is funding a range of large CPS-related projects, agencies such as DoT, DoE, and DHS are implementing mission-specific pograms for e.g. transportation, energy, and CPS security, and NIST has established the Cyber-Physical Systems and Smart Grid Program Office that coordinates its CPS efforts, such as the establishment of a Public Working Group (CPS PWG), the development of a CPS Framework in partnership with industry, academic and government experts, and the establishment of a CPS test bed program. In addition, industrial companies and industry-led associations drive CPS R&I efforts, e.g. the *Smart Manufacturing Leadership Coalition* (*SMLC*), the *Conference of European Directors of Roads* (*CEDR*), and others.

The US definition of CPS is somewhat different to the one generally used in the EU. While EU definitions clearly separate between embedded systems and cyber-physical systems, in the US, CPS are often seen as an extension of embedded systems, as e.g. illustrated by the CPS definitions in (10) and (11). Like in the EU, the US has realized that the benefits of the development and deployment of novel *NIT* (*Networking and Information Technology*, which is the US equivalent of the European term ICT) technologies such as CPS in the coming years and decades is enormous (11), and that IoT advancements will be a crucial enabler for CPS in a large variety of application domains (12). In fact, in the US view the IoT is often seen as a specific example of a CPS, while these two concepts are separated more clearly in the EU. Current US national priorities include health, energy, manufacturing, education, and privacy (10).

2.3.1. Research and Innovation Priorities in the EU

This section summarizes the major research and innovation priorities in the EU in the areas of cyber-physical systems (CPS) and cyber-physical systems of systems (CPSoS).

The major research and innovation priorities in the EU were identified based on different sources. In addition to input by the members of the IoT/CPS Expert Group, inputs that were obtained during feedback collection and personal interviews with funding agencies, industry associations, and individual researchers and practitioners, and PICASSO reports such as (1), relevant strategic documents and roadmaps were analyzed. These include the *Strategic Research Agenda 2016* of the *ARTEMIS IA* (7)**,** the *European Roadmap for Industrial Process Automation* that was developed by the EU project *Process.IT* (13), materials that were prepared during workshops of the EU project *Road2CPS* (14), and the brochure *Proposal of a European Research and Innovation Agenda on Cyber-physical Systems of Systems, 2016-2025* that was published by the consortium of the EU project *CPSoS* (15). In addition, 46 R&I projects were analyzed that are funded by EU-level initiatives including *FP7*, *H2020*, *EUREKA/ITEA*, *ECSEL-JU*, and *ARTEMIS IA*, 37 of which were found to relate to the technological topics described in the following.

Overall, nine R&I priorities were identified, four of which are mentioned in all strategic documents that were analyzed while the fifth topic was mentioned in three of the four analyzed documents. Another three topics are mentioned in two documents while two more topics are seen as important in only a single document. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

High-priority Research and Innovation Topics

Four topics are pushed as R&I priorities in all four of the analyzed strategic documents:

1. **(Systems) engineering support for highly dynamic, continuously evolving CPS:** This topic covers all aspects that relate to the engineering for modern CPS and CPSoS. Subtopics include
    - Integrated, virtual engineering of CPSoS over their full life-cycle
    - More agile and shorter development cycles for CPS
    - Heterogeneous modeling of CPS, which covers modeling-related challenges such as model evolution and adaptation, model maintenance, data-based and grey-box modeling, open simulation platforms and formalisms, simulator interoperability and co-simulation, stochastic models, modeling of human behaviors, integration of safety and security aspects into models, and access to user-friendly modeling tools

    Overall, 13 R&I projects were identified that deal with systems engineering support for CPS, which is the largest number for any of the EU CPS R&I priorities.

2. **Trust, (cyber-)security, robustness, resilience, and dependability:** Subtopics include
    - Secure real-time and mixed-criticality systems
    - Resilience to physical attacks
    - Intrusion detection and prevention
    - Certification and component-based recertification of high-dependability applications
    - Trust in large distributed systems

    7 R&I projects were identified in this area, most of which deal with secure real-time and mixed-criticality systems.

3. **Seamless integration, interoperability, flexibility, reconfiguration:** Subtopics include
    - Semantic interoperability, which ensures that different physical artefacts and computing elements 'understand' each other, even if they are implemented in different languages, tools, or platforms
    - Increasing openness and pushing open platforms (while retaining security and safety properties)
    - Auto-reconfiguration, adaptation of CPS elements, e.g. based on learned operational patterns from past examples / historical data
    - Opportunistic flexibility, i.e. taking advantage of the currently accessible opportunities to dynamically improve the quality of service

    4 R&I projects were identified in this area.

4. **Autonomy and humans in the loop:** Subtopics include
    - Socio-technical aspects of CPS
    - Autonomous CPS subsystems and their interaction with human operators
    - Analysis of user behavior, detection of needs and anomalities
    - Visualization and decision support, novel usability and HMI concepts to enable human operators to digest and react to large amounts of data and information quickly and effectively

    One R&I project was identified in this area.

In addition, the following topic was identified as a priority in 3 of the 4 analyzed documents:

5. **Situational awareness in large-scale CPS:** Subtopics include

- Real-time monitoring, exception handling, fault detection, and mitigation of faults and degradation
- Large-scale, real-time data analytics
- Learning, adaptive behavior, and self-diagnosis tools
- Predictive condition monitoring and maintenance

In this area, 3 R&I projects were identified.

Lower-priority Research and Innovation Topics

In addition to the five high-priority topics given above, other topics were identified as important, even though they were only identified in 2 of the strategic documents that were analyzed. These topics are:

6. **Distributed, reliable, and efficient management, control, and automation:** This topic was identified as a priority in 2 of the 4 analyzed documents. Subtopics include
    - Self-organization and structure formation
    - Emerging behavior, deriving e.g. from interactions of autonomous agents
    - Cloud-based real-time control

    In this area, 7 R&I projects were identified.
7. **Validation, verification, and computation of key properties of CPS:** This topic was identified as a priority in 2 of the 4 analyzed documents. 1 R&I project was identified in this area.

In addition, two topics were identified that are mentioned in only a single strategic document. These topics are:

8. **CPS reference designs and architecture principles:** Subtopics include
    - Extending the use of digital platforms to build stronger eco-systems with new business models
    - Integration of functions across application contexts

    1 R&I project was identified in this area.
9. **Open R&I environments, test beds:** In this area, no R&I projects were identified.

2.3.2. Research and Innovation Priorities in the US

This section summarizes the major research and innovation priorities in the US in the areas of cyber-physical systems (CPS) and cyber-physical systems of systems (CPSoS).

The major research and innovation priorities in the US were identified based on inputs by the members of the IoT/CPS Expert Group, inputs that were obtained during feedback collection and personal interviews with funding agencies, industry associations, and individual researchers and practitioners, PICASSO reports, and an analysis of relevant strategic documents, roadmaps, and funded projects. The strategic documents that were analyzed include the report *Designing a Digital Future* by the *President's Council of Advisors on Science and Technology* (*PCAST*) (10), a *CPS Vision Statement* that was published by NITRD (11), the NIST report *Strategic R&D Opportunities for 21st Century CPS* (16), the *Action Plan* that was developed by the EU project *CPS Summit* (12), a White House memorandum on *Multi-Agency Science and Technology Priorities for the FY 2017 Budget* (17), and a workshop report on a bilateral US-German workshop on IoT/CPS that was held in 2016 in Washington DC (18).

In addition, 23 R&I projects were analyzed, most of which are funded by NSF. The projects were selected from the overall list of NSF-funded CPS projects, and only the largest (in terms of funding) projects were chosen that are relevant to Iot-driven large-scale CPS. 19 of these projects were found to relate to the technological topics described in the following.

Overall, ten R&I priorities were identified, seven of which are mentioned in at least three of the strategic documents that were analyzed. Another three topics are mentioned in only one or two roadmaps. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

High-priority Research and Innovation Topics

Seven topics are pushed as R&I priorities in at least three of the analyzed strategic documents:

1. **Privacy, cyber-security R&D, and trustworthiness of technical systems:** This topic is seen in several documents as having the highest priority overall. Subtopics include
    - Resilience to cyber-attacks
    - Defending cyber-infrastructure, such as civil and governmental communications networks, electrical power generation and distribution systems, financial systems, logistics, fuels, water, and emergency services
    - Realizing the benefits of collective personal information without compromising the privacy of individuals
    - Trust in technical systems

    In this area, 2 R&I projects were identified.

2. **Situational awareness, diagnostics, prognostics:** The major objectives of this topic are to identify, predict, learn from, and prevent or recover from faults in complex systems. Subtopics include
    - Large-scale data management and analysis
    - Machine learning
    - Real-time monitoring, fault detection and mitigation
    - Ensuring access to and retention of critical community research data collections

    In this area, 5 R&I projects were identified.

3. **Validation of novel technologies via prototypes and test beds:** this area, 2 R&I projects were identified.
4. **Effective and reliable system integration and interoperability:** Subtopics include
    - Semantic interoperability between elements constructed in different formalisms, tools, engineering domains, and sectors
    - Abstractions, modularity and composability to enable a reliable and verifiable assembly of individual CPS elements

    In this area, 1 R&I project was identified.

5. **Autonomy and human-computer interaction:** Subtopics include
    a. Socio-technical aspects of CPS, i.e. leveraging the interaction between people and technology, and between complex infrastructures and human behavior
    b. Models and approaches for autonomous CPS systems, and of humans interacting with them
    c. Social computing to develop novel approaches to enable social collaboration and problem-solving in a networked, online environment

    1 R&I project was identified in this area.

6. **Model-based systems science and engineering methodologies**: Subtopics include
    - Systems engineering based architectures and standards to enable efficient design and development of reliability systems while ensuring interoperability and integration with legacy systems
    - Development of a mature systems science for high-confidence CPS
    - Conceptualizations of the deep interdependencies among engineered systems and the natural world
    - System-wide design
    - Heterogeneous CPS models, which includes modeling-related challenges such as the integration of multi-physics models and models of software to enable co-design of physical engineered and computational elements, common terminologies, modeling languages, and rigorous semantics for describing interactions across heterogeneous systems, and stochastics and uncertainty in models

    1 R&I project was identified in this area.
7. **Validation, verification, and certification:** Subtopics include
    - Rapid online (re-)verification and real-time health monitoring approaches
    - Time-critical and mixed-criticality architectures
    - Dealing with uncertainty, safety, and risk

    In this area, 2 R&I projects were identified.

Lower-priority Research and Innovation Topics

Three R&I topics were identified in two or fewer strategic documents:

8. **Educational technology, education and training for cross-disciplinary CPS:** This topic represents the challenge that science and engineering of CPS are cross-disciplinary in nature, requiring expertise in computer science, mathematics, statistics, engineering, and many other disciplines. Thus, new dynamic, multi-disciplinary education and training approaches and tools are needed to educate a skilled workforce for future CPS.

    In this area, no R&I projects were identified.
9. **Distributed control**, e.g. in the form of adaptive and predictive hierarchical hybrid control, is required to achieve tightly coordinated and synchronized actions and interactions in systems that are intrinsically asynchronous, distributed, and noisy.

    In this area, 4 R&I projects were identified.
10. **Open reference architectures** are needed to create universal definitions for representing ultra-large heterogeneous systems.

    In this area, 1 R&I project was identified.

2.4. The Internet of Things (IoT)

According to a recent European Commission study, the generating market value of the IoT in the EU is expected to exceed one trillion euros in 2020. Consequently, the IoT, like CPS, is a key pillar of the European *Digital Single Market Strategy*, the *Digitising European Industry* initiative, and the innovation programme *Smart Anything Everywhere*. The *Alliance for the Internet of Things* (*AIOTI*) was launched by the EC and key European IoT players in 2015 to develop and support the dialogue and interaction among the various IoT actors in Europe and to facilitate the creation of a European IoT ecosystem, with IoT large-scale pilots being funded to promote IoT take up. The IoT ecosystem is built on the work of the *IoT European Research Cluster* (*IERC*), which brings together 40 EU-funded projects with the aim of defining a common vision, identifying common research challenges and coordinating and encouraging the convergence of ongoing work. In addition, there are other initiatives such as *FIWARE* or *UniversAAL* which are providing open architectures and specifications to allow developers, service providers, enterprises, and other organizations to develop IoT products, as well as 16 cross-sectoral *Future Internet Accelerators* that address different application sectors such as Smart Cities, E-Health, Transport, Energy and Environment, and Manufacturing and Logistics, and others. EU-level initiatives are complemented by national programmes such as Germany's *Industrie 4.0* platform, the UK's IoT initiative, France's '*objets connectés*' and Spain's smart city initiative.

In the US, IoT developments are largely driven by companies instead of R&I programmes or federal agencies, with major players being Google, Cisco, Samsung, and others. The *Department of Commerce* (*DoC*), which estimates that digitization, of which the future of the IoT is a major part, has the potential to boost annual US GDP by up to $2.2 trillion by 2025 (19), is promoting growth of the digital economy and as part of the Digital Economy Agenda. The uptake of IoT technologies is promoted via various industry-driven consortia and alliances that include the *Industrial Internet Consortium* (*IIC*), the *Allseen Alliance* (that is dedicated to providing an open environment for the Internet of Things), and the *Open Connectivity Foundation* (*OCF*) that was founded by major companies (Intel, Microsoft, Samsung, Qualcomm, GE Digital, and Cisco Systems) to work towards a single standard for IoT.

2.4.1. Research and Innovation Priorities in the EU

This section summarizes the major research and innovation priorities in the EU on the Internet of Things (IoT), from the viewpoint that the IoT will be an enabler for future CPS. Thus, topics that relate to enabling technologies (see above), such as communication technologies, are not covered in the following.

The major IoT research and innovation priorities in the EU were identified based on different sources. In addition to input by the members of the IoT/CPS Expert Group and PICASSO reports, relevant strategic documents and roadmaps were analyzed. The main source was the book *Digitising the Industry* that was edited by senior representatives of the AIOTI alliance (8). Furthermore, the *EU-China Joint White Paper on the Internet of Things* by the *EU-China IoT Advisory Group* (20), three white papers by the internationally oriented *IIC* (6) (21) (22), and the roadmap by the EU project *Process.IT* (13) were considered. In addition, 32 R&I projects were analyzed that are funded by EU-level initiatives including *FP7*, *H2020*, *EUREKA/ITEA*, *ECSEL-JU*, and *ARTEMIS IA*. 14 of these projects were found to relate to the technological topics described in the following.

Overall, seven R&I priorities were identified, two of which are mentioned in more than one of the strategic documents that were analyzed. Another four topics are identified in only one of the strategic roadmaps, and one topic was identified based on funded projects alone. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

High-priority Research and Innovation Topics

Two topics are pushed as R&I priorities in at least two of the analyzed strategic documents:

1. **Automatic, semantic interoperability and integration of heterogeneous systems and platforms:** Subtopics include
    - Data semantics, semantic models, semantic integration
    - Automatic configuration

   In this area, 4 R&I projects were identified.

2. **Open architectures, platforms, and innovation ecosystems:** Subtopics include
    - Open IoT architectures and cross-domain infrastructures
    - Standarization and certification

   In this area, 2 R&I projects were identified.

3. **Closing the loop - creating a reliable monitoring/actuating IoT substrate:** This topic goes beyond pure connectivity and covers the challenges that arise when trying to transform the deluge of data provided by IoT-connected systems into knowledge and useful actions. This topic is seen as the most demanding IoT "macro-challenge" in (8). Subtopics include
    - Real-time data processing and analytics, i.e. novel methods and tools to transformation data into useful and actionable knowledge
    - Distributed/decentralized reasoning, low-latency cognitive (feedback) loops
    - Humans in the loop and self-management of IoT systems

   In this area, 1 R&I project was identified.

4. **End-to-end IoT security, trust, dependability, and privacy**, for which 1 R&I project was identified.

Lower-priority Research and Innovation Topics

In addition to the high-priority topics, two topics were identified that appear in one of the strategic documents.

5. **Large-scale test beds and pilots**, such as the ones provided by the initiatives *FIWARE* and *FIRE*. 5 R&I projects were identified in this area.
6. **Fully autonomous IoT devices**, for which no R&I project was identified.

One more topic was identified that was not mentioned in any strategic documents:

7. **Smart machine-to-machine (M2M) networks**, for which 1 R&I project was identified.

2.4.2. Research and Innovation Priorities in the US

This section summarizes the major research and innovation priorities in the US on the Internet of Things (IoT). As in the previous section, the topics reflect the viewpoint that IoT will be an enabler for future CPS, and topics that relate to enabling technologies are not covered.

The major IoT research and innovation priorities in the US were identified based on different sources. In addition to input by the members of the IoT/CPS Expert Group and PICASSO reports, relevant strategic documents were analyzed. Due to the current lack of involvement of federal and governmental agencies and programmes in IoT, comprehensive roadmaps are difficult to find in this sector. However, several white papers are available by the internationally oriented *IIC* (6) (21) (22) and by the company *Samsung* (9) that were analyzed, plus a few more general strategic documents that were published by governmental agencies such as the *DoC* (19), the White House (17), and the US Senate (23). In addition, 23 R&I projects were analyzed that are mostly funded by the NSF. 12 of these projects were found to relate to the technological topics described in the following.

Overall, five R&I priorities were identified, three of which are mentioned in at least three of the strategic documents that were analyzed. Another two topics are identified in two or fewer of the strategic documents. Note that in the following, the item numbers do not indicate priority, but only serve to make the items easily referable.

High-priority Research and Innovation Topics

Three priorities are identified in three or more of the strategic documents that were analyzed:

1. **Open architectures, platforms, interoperability:** This topic is seen as highly important, e.g. the DoC sees IoT openness as a grand policy challenge and states that "a free and open global Internet, with minimal barriers to the flow of data and services across borders, is the lynchpin of the digital economy's success". Subtopics include
    - Semantic technologies, semantic models, semantic integration
    - Novel IoT architectures and cross-domain infrastructures
    - Innovation ecosystems

   In this area, 7 R&I projects were identified.
2. **(Cyber-)security, privacy, resilience to faults/attacks, trust:** Subtopics include
    - Risk assessment and management
    - Fault and outage detection
    - Trust and security online
    - Robustification and additional security capabilities of legacy systems in industrial environments
    - Consumer protection

   In this area, 5 R&I projects were identified.
3. **Closing the loop: IoT as an enabler for future CPS:** This topic is very similar to topic 3 in the IoT-EU list above and covers the challenges that arise when trying to transform the deluge of data provided by IoT-connected systems into knowledge and useful actions. Subtopics include
    - Tools and platforms for real-time data analytics and transmission
    - Site-wide integration and convergence of control systems with *information technology* (*IT*) and *operational technology* (*OT*) systems
    - IoT edge devices / smart assets
    - IoT-enabled predictive maintenance and remote monitoring

   In this area, no R&I projects were identified.

Lower-priority Research and Innovation Topics

Another two topics are identified in two or less of the strategic documents:

4. **Human-centered IoT systems**, which acknowledges the fact that human capital remains critical to decision support. No R&I projects were identified in this area.
5. **Promotion of skill-building initiatives**, such as the National Initiative for Cyber Education (NICE). No R&I projects were identified in this area.

2.5. Application Sectors: Drivers and Needs

This section briefly summarizes the major drivers and needs in the application sectors of smart production (which includes smart manufacturing and processing, but not other types of production such as smart farming), smart cities, smart energy, and smart transport. This section is partly based on the PICASSO report (1) that provides a comprehensive survey of three of the four sectors as well as feedback by industrial interview contacts, and on inputs by the IoT/CPS Expert Group and external experts. In addition, the strategic documents and roadmaps that were used to create the survey in sections 2.3 and 2.4 were analyzed for application-relevant information. The results were validated during the feedback collection process.

While each vertical industry and application sector has unique needs (see e.g. (21)), research and innovation actors in both the EU and the US are aware that there are many cross-cutting R&I challenges in IoT and CPS, the solutions to which will benefit multiple sectors. As an example, *NITRD* (11) states in its CPS vision statement that "attempts to establish extensible architectures for unmanned aerial vehicles or self-driving cars in the transportation sector will directly benefit the designers of networked industrial control systems in manufacturing". On the EU side, the research agenda proposed by the *CPSoS* project (15) is an example of this fact, since only four of the R&I priorities they propose target specific application sectors while seven priorities are cross-cutting. Consequently, we have also found in interviews with companies and research institutes (1) that there is a general interest in all of the PICASSO application sectors. As examples, topics such as increased connectivity, increased autonomy, and the need for assurance and cyber-security are seen as being relevant for all application domains.

2.5.1. Smart Production

Making progress on advanced manufacturing and smart production systems is seen as essential in both the EU and the US. Current key drivers in this area are the German initiative *Industrie 4.0* in the EU and the *Industrial Internet of Things (IIoT)* in the US.

Production systems are currently evolving into global, highly integrated cyber-physical systems of systems that go beyond pure production and that cover all parts of the value chain. This evolution is driven by quickly changing customer requirements that are more aware of environmental impact, ask for a high degree of product customization and configurability, and require efficient, yet sustainable production. Major drivers in the production sector are the trend towards zero-waste and environmentally neutral processes and plants, efficient resource usage, site-wide optimal operation, high availability and safety, increases in complexity and flexibility with reduced time to market, and the need for a highly skilled work force for the design and operation of modern production systems.

Novel ICT technologies, in particular CPS technologies and the (industrial) IoT, are seen as vital to preserve the competitiveness on both sides of the Atlantic (15), (11). The major needs in the smart production sector are:

- **Interoperability and standardization:** Production systems consist of thousands of (often proprietary) hardware and cyber components by a large number of manufacturers that have to be integrated with each other and with legacy systems. Interoperability is a key prerequisite for novel ICT technologies that will require global real-time access to all devices at the field and automation levels. Thus, challenges such as plug-and-play reconfiguration, zero-configuration integration of automation systems, real-time analytics and optimization, monitoring and diagnostics, and others depend on the interoperability of technical systems. There is a need for companies to move away from proprietary solutions towards open interfaces and platforms. The production of *Industrie 4.0* compatible automation products is seen as an opportunity for harmonization within the industry, and the expectation is that the cloud and the *IIoT* will be used to connect smart components. Another need that is currently arising is that of complete value chain integration of production systems.
- **Exploiting the IoT - Real-time analytics, situational awareness, predictive maintenance, data-based operation/optimization:** The availability of IoT-connected, financially viable sensors, software and devices will enable manufacturers to generate compelling business value. There is thus an opportunity for automation systems and optimization of processes based on much greater collection of data. Monitoring is also seen as a key driver for the industry. There are many new ideas being promoted such as the "augmented operator" where information is provided to wearables, smart phones, and other smart devices. This is being used to provide information for optimization, asset management, and predictive maintenance to operators as they walk around the factory. A success story by Intel provides a good case for the enormous business value that can be added based on data and real-time analytics (22): In one of its factories, Intel installed sensors on CPU assembly modules that are employed in the

final steps of CPU manufacturing. Using analytics software, Intel was able to reduce the number of machine failures, detect defects on the assembly line, and boost assembly line uptime and productivity. This led to a time and inspection effort reduction by a staggering 90 percent.

- **Cyber-security** is quickly becoming the key issue in smart production with the advent of ubiquitous connectivity in industrial environments.
- **Integrated management and control structures, system-wide management:** With increasing complexity and integration in large production systems, decentralized and system-wide control and management of production complexes will become a major need, with a key area being management to improve energy efficiency. More generally, increases of automation in production systems have additional advantages, such as the reduction of human exposure to dangerous areas through remote operation, and the reduction of personnel requirements (e.g. night shift operators) for the 24/7 operation in production complexes that are never switched off, such as chemical plants.
- **Integrated engineering approaches for cyber-physical systems** is a key need to enable engineers to deal with the challenges that arise from the complexity, quick evolution, and required flexibility of modern production systems. In addition, supply and value chain integration is an important topic in the smart production sector.

The feedback that we have obtained so far indicates that it is (at least potentially) possible for the EU and US to work together in all technological areas of smart production. However, in the production sector there are conflicting strategic and commercial interests between both sides that will be significant barriers, with a major challenge being to find partners who are willing to collaborate.

2.5.2. Smart Cities

The Smart Cities industry is estimated to be valued at more than $400 billion globally by 2020. In contrast to other sectors, the scope that is covered under the smart city keyword is often not clearly defined, and the area of smart cities consequently may cover a very wide scope that goes beyond interactions with citizens and use of their data to also include control and management of energy, waste, buildings, utilities, and infrastructure, as well as social interactions with government, education, and e-health. In some definitions, smart energy and smart transportation are also seen as part of smart cities. These sectors are described later below.

Major drivers in this sector are reductions in greenhouse gas emissions (*decarbonization*), the needs for clean air and water, the need for increased security and safety, efficient use of space, infrastructure, and other resources, globalization, the trend towards migration to cities, increases in autonomous functionality and connectivity, and advances in artificial intelligence.

The major needs in the smart cities sector that will benefit from the development and deployment of novel IoT and CPS technologies are:

- **Interoperability and integration** (of data and infrastructures) is seen as a major challenge. Due to the increase in connectivity, concepts such as integrated smart transportation systems are receiving widespread attention.
- **Cyber-security, safety, and privacy:** As in the other application sectors, cyber-security is seen as a major challenge for smart city platforms and applications. In addition, guaranteeing privacy is essential due to the strong involvement of private citizens.
- **(Real-time) data analytics:** The spread of connectivity are expected to enable novel concepts and solutions for smart city applications such as smart lighting (“Internet of Lighting”), smart building management (“Internet of Buildings”), smart garbage collection, optimal use of water and energy, and monitoring for the safety and well-being of inhabitants.

- **IoT platforms for smart city applications.**

The feedback that we have obtained so far indicates that it is likely that there are collaboration opportunities on different topics, such as interoperability of data, infrastructures, cloud computing, and real-time data analytics. Collaboration on privacy and security topics may be difficult due to differences in regulations and strategic interests.

2.5.3. Smart Energy

The energy sectors in the EU the US have high demands for quality, repeatability and performance, and are mainly driven by green initiatives and the decarbonization of the grid, e.g. in Europe to reduce greenhouse gas emissions by 40% by 2030. The inclusion of renewables and decentralized production are major drivers, as is the improvement of grid stability.

ICT is already exploited in many areas within the energy supply sector and is used to provide availability of services, for management to reduce consumption and CO_2 emissions, to improve stability and safety, and to integrate renewables. The move to the IoT is seen as a key driver in both the EU and the US. For example, PG&E has created the new moniker *Grid of Things* to make the IoT more applicable to utilities, and in Europe the "Internet of Energy" term has been coined. Furthermore, CPS technologies are seen as important for the creation of a smart infrastructure for realizing a smart grid, enabling the optimization and management of resources and facilities and allowing consumers to control and manage their energy consumption.

The major needs in the smart energy sector that will benefit from the development and deployment of novel IoT and CPS technologies are:

- **Cyber-security and safety:** As in the other application sectors, cyber-security is seen as a major challenge for smart energy applications.
- **Novel approaches for the engineering and dynamic management of smart grids with decentralized production / renewables:** There is a major need for novel engineering and dynamic power management methodologies for applications ranging from single devices to complete grids, including using real-time data for optimal energy management.
- **Interoperability and harmonization of standards:** Currently, standards for interoperability are being driven by the EC and EFTA on the EU side and NIST and FERC on the US side. A challenge is the harmonization of interoperability standards developments.
- **Exploiting the IoT and intelligent connectivity for smart grid applications.**

The feedback that we have obtained so far indicates that there is significant pessimism with respect to collaboration opportunities due to differences in the grid topologies, standards, and technologies between the EU and the US, and due to differences in the requirements for Smart Grids (1). However, there may be opportunities for joint research in the areas of smart metering, energy efficiency and management, low-carbon economy, and renewable energy. The *BILAT USA 4.0* project (24) has found that there is interest from EU and US partners in advancing already existing collaborations around energy.

2.5.4. Smart Transportation

The sector of smart transportation covers several modes, i.e. road/automotive, rail, aerospace, and maritime. North America and Europe are expected to become the largest markets for ITS (Intelligent Traffic Systems). Within Europe, sustainability (via the promotion of e.g. electric mobility / decarbonization of transport) is a key driver, with a dramatic anticipated increase in both freight and passenger transport and associated emissions. Other drivers are to reduce casualties (for which autonomous mobility is pushed) and to reduce congestion via ITS. To achieve these goals, EU programmes of enormous size have been set up, such as the Trans-European

Transport Networks (TEN-T) policy with an investment volume of € 400 billion. The drivers in the US are similar to the European ones, with the added driver of homeland security.

ICT is already being used in smart transportation to provide an optimized use of infrastructure to increase capacity and also to improve the safety of road transport, e.g. via traffic management systems that are relying on increased connectivity between cars and between cars and infrastructure. The consensus is that there is an urgent need to deploy novel ICT technologies, such as CPS technologies, to improve efficiency and safety in transportation, with a notable opportunity being increased autonomy which is expected to lead to fundamental changes to traffic operation.

The major needs in the smart transportation sector that will benefit from the development and deployment of novel IoT and CPS technologies are:

- **Interoperability:** There are several areas in which interoperability between heterogeneous transportation systems is essential. These include the uniform compatibility of electric vehicle charging stations with all electric vehicles from the EU and the US, standards and protocols for vehicle-to-vehicle (V2V) communication, integration and compatibility of vehicle-to-infrastructure (V2I) systems (including interoperable interfaces for roadside infrastructure), and harmonized information exchange between transportation systems from the maritime domain. There is also a need for future automation system architectures to be more open.
- **(Cyber-)security and safety:** As in the other application sectors, cyber-security is seen as a major challenge for smart transportation applications. Approaches to mixed criticality are another need here.
- **Intelligent traffic management, drive-by-wire vehicles, autonomy:** ICT is needed for the optimized use of transport infrastructure to increase capacity and to improve safety, using e.g. data collection and processing and new technologies for autonomous vehicles.
- **Systems engineering and supply chain integration**, including interoperability of tools, integration of engineering domains, integration of different disciplines across the supply chain, and integrated systems engineering approaches for future transportation infrastructures.

In addition, education and training of a high-skill work force was identified in several of the transportation domains as a major need for the future.

There is already considerable joint work going on between the EU and US, e.g. developing interoperability of charging stations. In addition, an implementation agreement was signed to boost cooperative activities in the field of research, technology and innovation for all modes of transport (24). Key areas include freight transport and logistics, sustainability, safe and seamless mobility, road traffic management, and human factors. Our analysis (1) showed that further EU-US collaboration might be possible on challenges such as traffic management, autonomous and electric cars, integration of vehicle and infrastructure systems, traffic management using ITS, data collection and processing, and model-based systems engineering.

2.6. Analysis

This section summarizes major conclusions from the overview of the drivers, needs, and research and innovation priorities in the EU and the US that was presented above.

1. The intersection of the IoT and future CPS is an important challenge and opportunity in both the EU and the US.

The CPS and IoT domains are vast, and the development of concrete and feasible collaboration opportunities is only possible by restricting our focus on subsets of these domains. Our analysis has revealed that restricting the scope of the PICASSO work on IoT/CPS to the intersection of the IoT and CPS is a good option, as it is of high relevance in both the EU and the US, and the IoT is seen as an important driver for the design and operation of future CPS.

In the EU, this challenge is recognized by several institutions, such as *the ARTEMIS Industry Association* who believe that the "Internet of Things, and consequently the Things of the Internet, and Cyber-Physical Systems are complementary directions which together will help to shape a society where humans and machines increasingly interact to provide services and solutions for the benefit of society that are inconceivable with the present state-of-the-art technology" (7), and the *European Alliance of IoT Innovation* (*AIOTI*) who see this as a macro-challenge, stating "Getting billions of objects duly connected and managing these to create a reliable monitoring/actuating substrate only partially caters for the challenges ahead. These challenges cannot be complete without considering how to handle the huge amount of data produced and how to transform it into useful and actionable knowledge." (8). On the US side, for example the *Industrial Internet Consortium* (*IIC*) promotes the message that "Companies need to close the loop across associated processes." (6), the US branch of Samsung sees the CPS draft framework by NIST as an important prerequisite for the future of IoT (9), and the NSF is currently funding several research projects that cover the idea of using the IoT as an enabler for CPS.

The IoT/CPS feedback collection process, and in particular the personal interviews that were conducted with senior EU and US representatives, strongly reinforced the importance of the intersection of the IoT and future CPS. All interview partners who were asked about this agreed that this is one of the major challenges in IoT and CPS going forward, both in the EU and the US.

2. There is a significant overlap between R&I priorities in CPS between the EU and the US.

When comparing the R&I priorities between the EU and the US in the CPS area (see Figure 2), it becomes apparent that EU and US actors have identified similar challenges and priorities.

In particular, a comparison of the results shows that five R&I priorities are of high relevance in both the EU and the US:

- Model-based systems engineering
- Trust, (cyber-)security, robustness, resilience, and dependability
- Integration, interoperability, flexibility, and reconfiguration
- Autonomy and humans in the loop
- Situational awareness, diagnostics, and prognostics

In addition, the following common topics of lower priority were identified:

- Validation and verification
- Distributed, reliable, and efficient management, control, and automation
- Open environments, test beds
- CPS reference designs and architecture principles

Our feedback collection efforts have shown that EU and US experts are in agreement with the R&I topics that have been identified in this analysis.

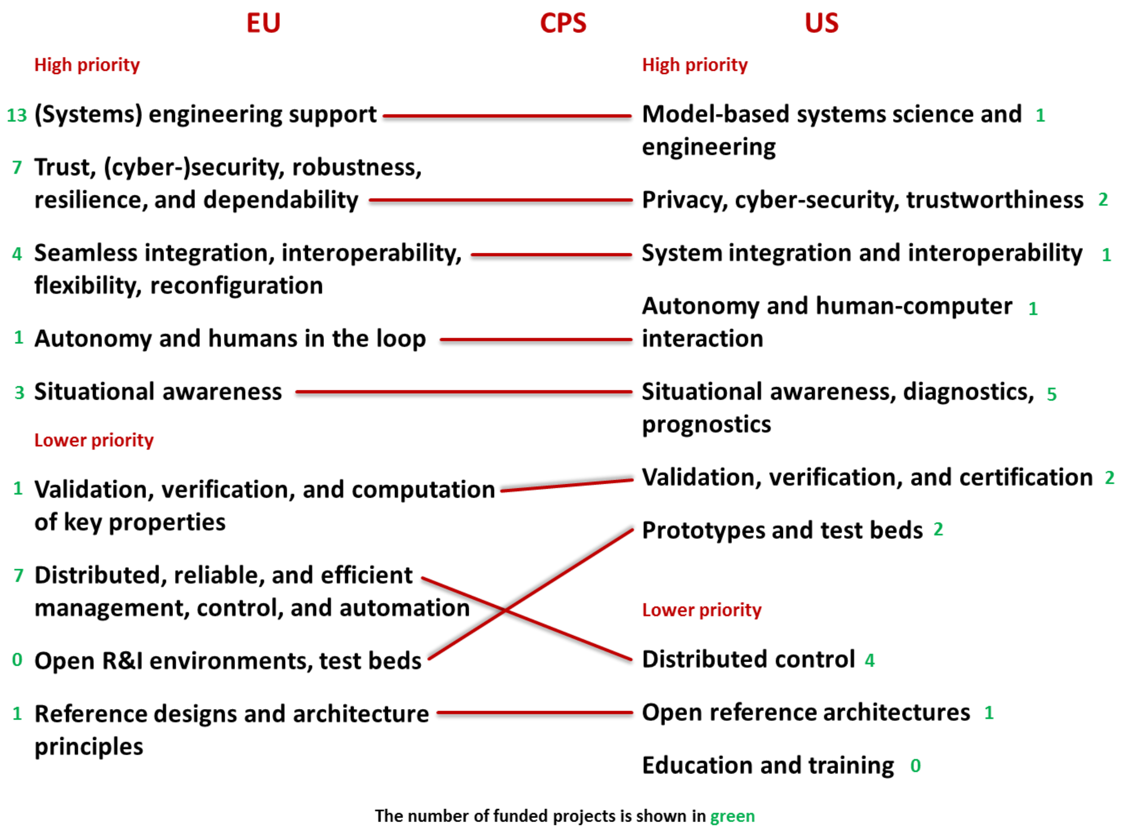

Figure 2: Comparison of CPS topics in the EU and the US.

An analysis of the funded R&I projects on these topics shows that:

- The important topics of **autonomy and human interactions** seem to be underfunded in both, the EU and the US. These topics should receive more funding, and there may be good opportunities for collaboration on these topics.
- Although management, control, and automation were not identified as high-priority topics in this analysis, the large number of projects that are funded in these areas indicate that this topic is seen as important.

3. There is a significant overlap between R&I priorities in IoT between the EU and the US.

There is a significant overlap of the R&I priorities between the EU and the US in the area of IoT (when focusing on topics that are most relevant to using the IoT to enable future CPS), as shown in Figure 3.

A comparison of the results shows that four R&I priorities are of high relevance in both the EU and the US:

- Interoperability and integration
- Closing the loop - IoT as an enabler for CPS
- (Cyber-)security, privacy, resilience to faults/attacks, trust
- Open architectures and platforms

Our feedback collection efforts have shown that EU and US experts are in agreement with the R&I topics that have been identified in this analysis.

An analysis of the funded R&I projects on IoT topics shows that

- The important topic of "closing the loop" seems to be severely underfunded in the IoT domain. This topic is essential for the future of IoT and CPS systems and should receive more funding, and there are very likely good opportunities for collaboration.
- In the EU, there is currently a strong push towards test beds and large-scale IoT pilots, which does not seem to be mirrored in the US (although recent documents indicate that focus will increase in the future).

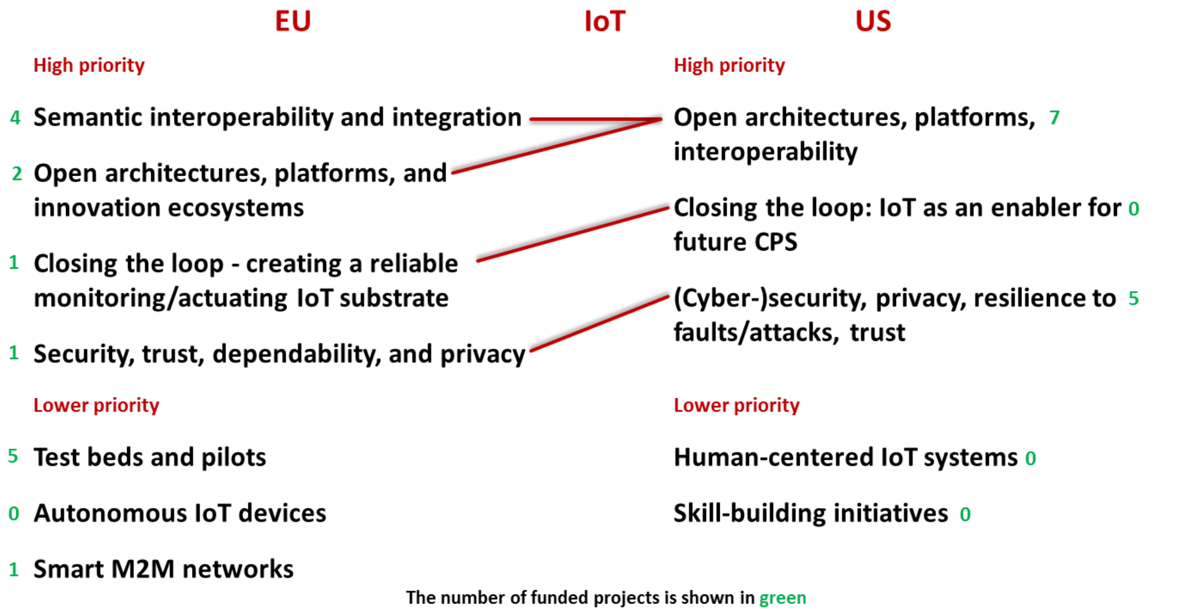

Figure 3: Comparison of IoT topics in the EU and the US.

4. Several R&I priorities are of high relevance in both the CPS and the IoT domains.

Figure 4 shows a comparison of, and mapping between, the high-priority R&I topics in the EU and the US. All of the high-priority IoT topics are linked to equivalent CPS topics, indicating that advancements of the state of the art in these topics will drive progress in both areas. There are several major conclusions that can be drawn from our analysis, and from the feedback that we have obtained from interviews, questionnaires, and the interactive webinar.

Over the last decades, different R&I areas have sprung up for CPS that all aim to provide methods, theories, and tools to compute useful knowledge and to generate useful actions, including model-based systems science and engineering, situational awareness, diagnosis, prognosis, monitoring, management, control, and automation, and validation and verification, and CPS researchers and practitioners have ample experience in these areas. In contrast, the topic of "closing the loop", i.e. processing data from IoT devices to transform it into useful and actionable knowledge, or into useful actions, is a relatively recent topic in IoT. One major conclusion from our feedback collection efforts is that while the experience that relates to this topic from the CPS arena is a good basis for future R&I efforts (in particular in management, control, and automation), the availability and ubiquity of IoT-connected devices will pose novel challenges that are not present in "pure" CPS, and the topic of **closing the loop in IoT-enabled CPS** is a promising target for future research, innovation, and collaboration efforts.

The topics of **cyber-security, privacy,** and **trust** (or **trustworthiness** as it is referred to in the US) are currently the dominant topics in the US, somewhat more so than in the EU. Recently strategic documents and our interviews indicate that these topics will become even more important in the future in both the EU and the US. Some of our interview contacts indicated (1) that it may be challenging to collaborate on privacy-related topics due to differences in interests and policy between the EU and the US, and collaboration on cyber-security topics may be difficult as well. However, technology-oriented research collaborations on related topics may be feasible, such as attack resilience and intrusion detection or secure real-time and mixed-criticality systems.

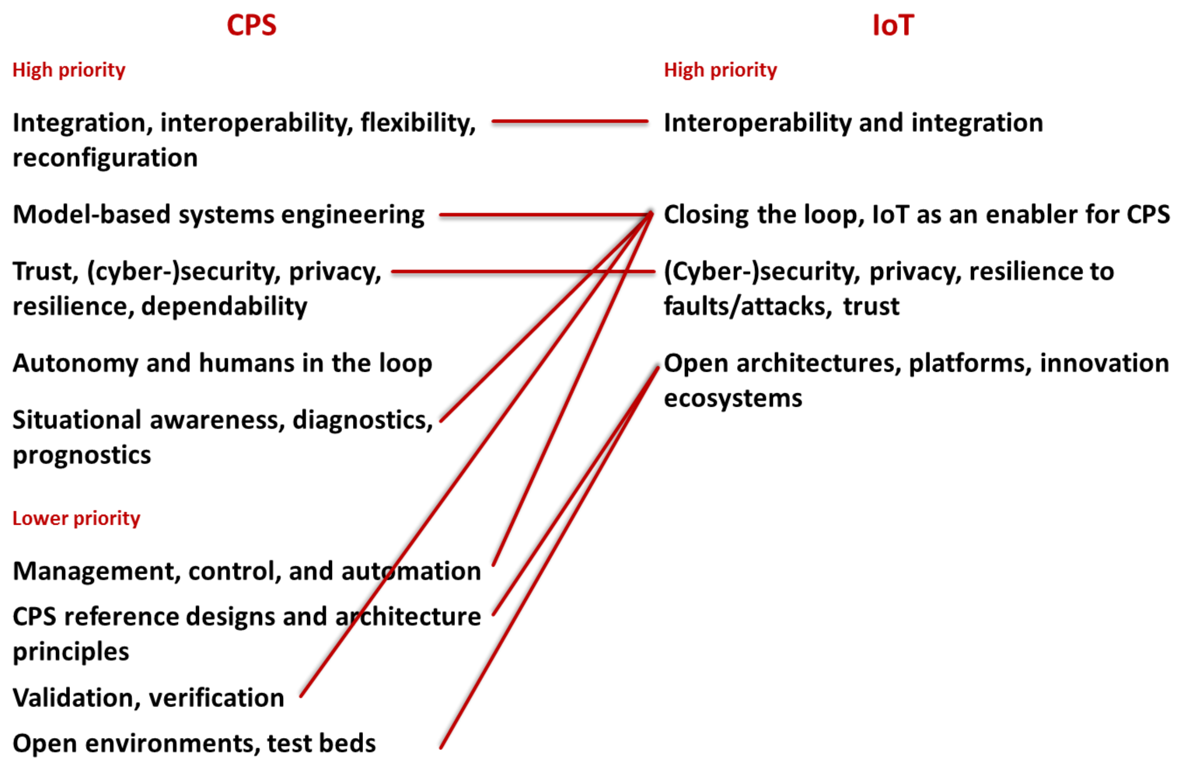

Figure 4: Mappings between CPS and IoT topics in the EU and the US.

Although this fact is not directly reflected in our analysis, our interviews indicate that there is currently a **strong push towards large-scale demonstrators and test beds** not only in the US, but also in the EU (see e.g. (25)), and the importance of joint test beds, demonstrators, and shared infrastructure in particular for EU-US collaboration was pointed out by several interview partners. Thus, this aspect is reinforced in the R&I themes in section 3 and in the collaboration opportunities defined below.

Another conclusion from our interviews and recently released strategic documents is that (**industry-driven) standardization activities** will gain importance in the next years, in particular in the quickly evolving IoT landscape, and that international collaboration will be essential to ensure interoperability and successful integration of future large-scale infrastructures.

Our findings are well aligned with those by other initiatives that work, or have worked, on the identification and promotion of R&I collaborations between the EU and the US, i.e. the EU project *DISCOVERY*[10] (26) that has the main objective to create a transatlantic ICT forum as a sustainable mechanism to support dialogues for EU-North America cooperation in the field of ICT, the EU project *TAMS4CPS*[11] (27) that focuses on modeling and simulation (M&S) for CPS, and the EU project *CPS Summit* (12). There are no contradictions between our results and the findings of these projects, and in particular the overlap with the findings of the *DISCOVERY* and the *CPS Summit* projects is significant (the limited scope of *TAMS4CPS* also restricts the breadth of their analysis).

DISCOVERY has just released a comprehensive survey of ICT research and innovation priorities (26) for which 123 EU and 46 US stakeholders were interviewed, including representatives from academia and industry, decision makers, government institutions, and associations. Out of the 10 most relevant ICT priorities that were identified, 7 relate directly to IoT or CPS and match well with the topics that PICASSO has identified. These priorities include

[10] http://discoveryproject.eu

[11] http://www.tams4cps.eu

privacy, data protection, and cyber-security R&I, threat detection and responses to cyber-attacks, model-centric and predictive engineering methods and tools for smart CPS, IoT integration and platforms, and new ICT platforms and technologies for smart buildings, smart grids, energy storage, electric vehicles, and smart charging infrastructures.

CPS Summit views the CPS foundational challenge as so great that a collaboration would prove to be beneficial for industry, academia, and governments, and it has identified the following technological challenges: the socio-technical character of CPS, systems theory and model-based systems engineering, cyber-security and dependability, interoperability, autonomy, technology platforms, data-driven approaches, verification and abstraction, dealing with uncertainty and risk, and humans in the loop.

5. All of the analyzed application sectors will profit from IoT/CPS advances and collaborations.

Our analysis has shown that institutions in both the EU and the US view CPS and IoT as pervasive technologies that will impact all application sectors and almost all aspects of life, and that **there are many cross-cutting challenges and needs in the four domains of smart production, smart cities, smart energy, and smart transportation**, as illustrated in Figure 5.

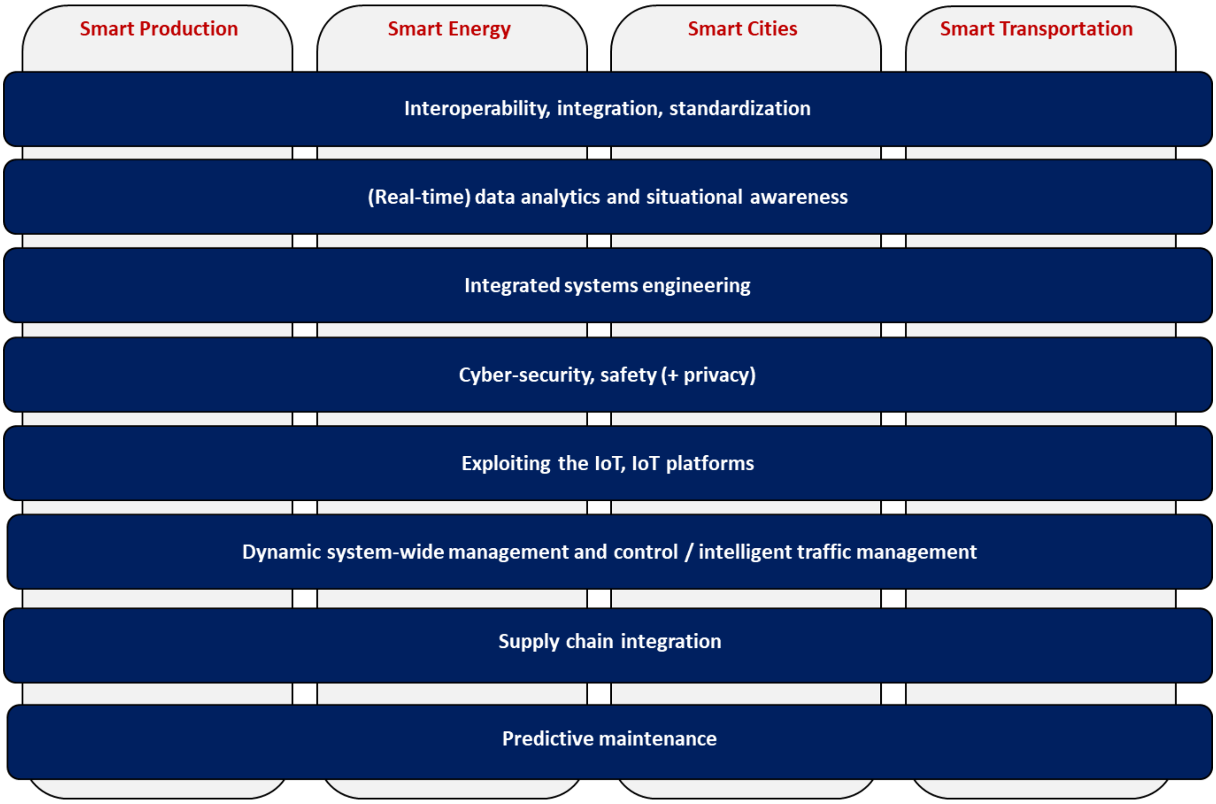

Figure 5: Identified major needs in IoT/CPS-relevant application sectors.

While this does not necessarily mean that all of these challenges can be served adequately by generic, cross-cutting solutions and platforms (since there are application-specific differences in many of the needs and environments of the sectors), it does indicate that the development of cross-cutting new technologies will provide significant benefit to different application sectors.

6. Our analyses, discussions, and interviews have shown that there is significant potential for collaboration on IoT/CPS topics between the EU and the US.

There are many similarities in drivers, needs, challenges, priorities, and programmes being pursued in the EU and the US. It is also clear that there are a number of opportunities where joint R&I between the EU and US would be beneficial, both on technological topics and on application topics, and our discussions with experts (1), members of the IoT/CPS Expert Group, and personal interview partners from funding agencies, industry, and academia indicate that there is willingness of collaboration between the EU and the US. In particular, lightweight collaboration mechanisms are currently favored, and both governmental and non-governmental (e.g. industry-led associations and multi-lateral companies) US actors were identified as promising collaboration partners for EU partners and projects.

This view is reinforced by other EU projects that work on promoting EU-US collaboration, such as the *CPS Summit*, *TAMS4CPS*, *DISCOVERY*, and *BILAT USA 4.0* projects. The latter project has e.g. found that ICT is the single most predominant area targeted for future EU-US cooperation, with promising topics including smart cities, the IoT, CPS, data management and open data, cognitive computing, automation, and cyber-security (24), and the *DISCOVERY* survey (26) shows that there are good perspectives for future EU-North America collaboration in ICT, especially under H2020 but also under US (and Canada) funding programmes, since a majority of respondents indicated interest in collaborative research and innovation.

3. Technology Themes for EU-US Collaboration

The analysis in section 2.6 has shown that there is a large overlap between the current R&I priorities in the EU and the US in the sectors of the IoT and CPS, as well as between the IoT and CPS sectors themselves. This section presents six R&I themes that were developed based on the analysis in section 2, and on discussions with the PICASSO Expert Group on IoT/CPS and with external experts from funding agencies, industry, industry-led associations, and academia.

In item (2) in section 2.6, five CPS-focused R&I themes were identified that have a high priority in both the EU and the US:

- Autonomy and humans in the loop
- Model-based systems engineering
- Trust, (cyber-)security, robustness, resilience, and dependability
- Integration, interoperability, flexibility, and reconfiguration
- Situational awareness, diagnostics, and prognostics

As illustrated in Figure 4 in section 2.6, these themes are related to the high-priority IoT topics, indicating that advancements in the state of the art in these topics will drive progress in both domains, in particular at the intersection of the IoT and CPS.

In addition, our analysis has provided strong evidence (see item (4) in section 2.6) that the R&I theme of "Closing the loop in IoT-enabled cyber-physical systems" is seen as an essential challenge in the EU and the US and that it offers interesting technological challenges that must be solved in the near future to enable the efficient usage of real-time data that is provided via IoT-connected devices.

Subsequent discussions within the Expert Group and with external stakeholders led to a prioritization of these technology themes with respect to their general importance, and to their importance for EU-US collaboration in particular. According to these discussions, the theme **Autonomy and Humans in the Loop** currently has the highest priority and should be in the focus on EU-US collaboration. Two other themes are currently of high importance as well according to our discussions, **Model-based Systems Engineering** and **Trust and Cyber Security**.

The remainder of this section presents draft summaries of all of the six R&I themes.

3.1. Autonomy and Humans in the Loop

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Autonomy in large-scale, complex, open systems, taking into account that such systems are not domain/knowledge-"contained"
- Models of autonomous CPS systems and humans
- Socio-technical aspects of IoT-driven CPS
    - Humans in the loop and collaborative decision making
    - Analysis of user behavior and detection of needs and anomalies
    - Novel approaches for analysis, visualization, and decision support

Why EU-US Collaboration?

Modern large-scale CPS are socio-technical in nature, and taking their interaction with humans into account has been identified as a challenge in both the EU and the US, as has the increasing trend towards autonomy in many areas and the need to predict how autonomous systems will behave when interacting with human actors. The significant overlap of the needs and interests in the EU and the US in this area is a good basis for R&I collaboration, a view that was reinforced during the feedback collection process. In addition, autonomy has recently gained much more importance within the EU R&I landscape, with "autonomous cyber-physical systems" likely becoming a major focus theme in H2020 and FP9.

Relevance to Application Sectors

Our analysis has shown that the need to consider the interactions of humans with technical systems is seen in several application sectors, and that there is an interest in the area of increased autonomy that cuts across all domains, in particular smart cities and smart transportation.

3.2. Model-based Systems Engineering

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Integrated, virtual, full-life-cycle engineering, system-wide design
- Engineering of high-confidence IoT and CPS systems, formal methods for assured design, validation, verification, risk analysis and risk management
- Models of heterogeneous large-scale systems
    - Open simulation and model integration platforms
    - Stochastic models
    - Model adaptation, maintenance, and validation
    - Data-based and grey-box modeling

Why EU-US Collaboration?

A consistent systems science and new integrated model-based engineering methodologies are of importance for the design, optimization, and operation of future IoT-enabled CPS. The documents that were analyzed show that the US view on this topic focuses more on theoretical aspects of systems science for novel CPS (such as the formal conceptualization of the interdependencies of technical systems and the environment) and on reliability aspects while the EU view seems to promote the practical aspects (such as integrated engineering of novel CPS) more, as well as system-wide management and coordination. These somewhat differing views are an argument for collaboration as EU and US groups may complement each other well in systems engineering R&I topics, which was confirmed during personal interviews conducted with senior experts from both sides. The challenges that are seen as important by both sides are similar (e.g. open simulation and model integration platforms and heterogeneous modeling of CPS), which may facilitate the identification of suitable collaboration partners.

Relevance to Application Sectors

Model-based systems engineering approaches and methodologies, as well as novel approaches for system-wide management and coordination, have been identified as major needs in all of the application sectors that we have analyzed.

3.3. Trust, (Cyber-)security, Robustness, Resilience, and Safety

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Exception handling, fault detection and mitigation
- Trustworthiness of technical systems regarding safety, reliability, privacy, and cyber-security
- Behavior-based methodologies to establish trust (e.g. via intrusion detection and prevention based on physical behaviors, resilience to cyber-attacks)
- New engineering perspectives for safety, security, resilience, reliability, and privacy
- Secure real-time and mixed-criticality systems

Why EU-US Collaboration?

Cyber-security is currently one of the dominant topics in the US, is seen as important in the EU as well, and will become even more important over the next years. Although collaboration on data-sensitive or privacy-related topics is most likely not feasible, our analyses and interviews indicate that technology-oriented R&I collaborations on topics such as cyber-security, trustworthiness, safety, attack resilience and intrusion detection, and secure real-time and mixed-criticality systems are seen as feasible and interesting. The large overlap in interests is a good basis for R&I collaborations.

Relevance to Application Sectors

The topics of cyber-security and safety are seen as the key challenges in all of the application sectors that we have analyzed. Thus, EU-US collaborations will benefit all sectors.

3.4. Integration, Interoperability, Flexibility, and Reconfiguration

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Semantic interoperability and semantic models (which ensure that different physical artefacts and computing elements 'understand' each other)
- Joint testbeds and large-scale pilots for CPS and IoT systems, shared infrastructure access
- Openness and open standards, harmonization of standards, establishing shared consensus as a basis for standardization activities
- Automatic configuration, reconfiguration, scalability, and plug-and-play integration of IoT and CPS components
- IoT and CPS architectures and cross-domain infrastructures

Why EU-US Collaboration?

The topics of integration, interoperability, flexibility, and reconfiguration were identified in our analyses as being of the high relevance in the EU and the US in both the CPS and the IoT domains. In particular, semantic interoperability and the need for consensus and open standards are seen as important in all domains and on both sides of the Atlantic. Joint testbeds, large-scale pilots, and shared infrastructure access were identified as essential tools to promote interoperability between heterogeneous infrastructures, and both the US and (in particular) the EU are currently working on large-scale demonstrators, e.g. in the areas of the IoT and smart cities, with indications that these efforts will be reinforced in the next years. IoT-based, next-gen infrastructures with cross national boundaries, which makes joint efforts for interoperability indispensable. The large overlap in topics, interests, and the suitability of shared infrastructure access for collaboration was confirmed during the feedback collection process (in particular in personal interviews with senior experts) and is a good basis for R&I collaboration.

Relevance to Application Sectors

The areas of interoperability and integration are of crucial importance in all of the application sectors that we have analyzed. Novel methodologies for (automatic) reconfiguration will be necessary for the development of future industrial infrastructures and networks, e.g. to reflect the increasing requirements for flexibility in manufacturing systems or to implement future smart grids with a large penetration of renewables.

3.5. Situational Awareness, Diagnostics, and Prognostics

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- Large-scale real-time data analytics and data management
- Machine learning, learning methodologies, adaptive behavior
- Predictive condition monitoring and maintenance
- Self-diagnosis tools

Why EU-US Collaboration?

With the increasing pervasiveness of affordable sensing devices in future IoT-enabled CPS and, the intelligent use of data will become crucial to deal with the increasing complexity and to ensure efficient and optimal operation. This fact has been recognized in both the EU and the US, and the large overlap of interests and needs in this area will facilitate the successful establishment of R&I collaborations.

Relevance to Application Sectors

The increasing use of data and of real-time data analytics for the optimization and monitoring of technical systems is seen as a major opportunity, or even a prerequisite, in all of the application sectors that we have identified. Thus, novel theories, tools, and methodologies in this area will benefit all of these application sectors.

3.6. Closing the Loop in IoT-enabled Cyber-physical Systems

Research and Innovation Topics

Potential topics in this area for EU-US collaboration are:

- System-wide management and coordination via IoT-connected devices
- Data-based operation
- Cloud-supported control and management
- Control architectures for IoT-enabled CPS

- Closed-loop control over nondeterministic, variable-delay networks - performance and stability in the face of unpredictability
- Closing the loop in the face of outages, limited bandwidth, latency, and jitter

Why EU-US Collaboration?

Going beyond pure connectivity and using IoT-connected devices for closed-loop applications in technical systems is an almost natural next step that will be the basis for new levels of efficiency, quality, and reliability in next-generation cyber-physical systems. Our analyses and interviews have shown that both the EU and the US technical communities are aware of the enormous potential benefits of "closing the loop" and see this as probably the major technological challenge going forward. It is also recognized that the IoT and future IoT-enabled infrastructures are inherently multi-national and that this challenge cannot be addressed unilaterally, thus making it an excellent subject for future EU-US collaboration activities.

Relevance to Application Sectors

The potential benefits that arise from exploiting the IoT are seen as major drivers for novel ICT developments in all of the application sectors that were analyzed, and closing the loop in IoT-enabled CPS will benefit a diverse range of application scenarios, ranging from future global, highly integrated production systems over smart city applications and the efficient integration of renewables into smart grids to transportation systems and networks for e.g. intelligent traffic management and autonomous driving.

4. Opportunities and Barriers for EU-US Collaboration in Technology Sectors

This chapter gives a brief overview of the EU-US funding and collaboration environments in section 4.1 and summarizes barriers that may hamper EU-US collaboration in section 4.2. Section 4.3 provides recommendations of concrete opportunities that were identified as the most promising mechanisms for technological collaborations on the R&I themes presented in chapter 3.

The contents of sections 4.1 and 4.2 were created by the IoT/CPS Expert Group (with inputs from the Big Data and 5G Expert Groups), and the contents of section 4.3 are based on these sections. Additional sources include inputs and pointers from numerous external experts from EU and US funding agencies, industry associations, and academia that were interviewed by the IoT/CPS Expert Group, the analyses presented in section 2, the PICASSO reports (1) and (2), materials and feedback by the EU projects *DISCOVERY* (26), *BILAT USA 2.0*, *BILAT USA 4.0, CPS Summit*, and *TAMS4CPS*, and the interactive PICASSO IoT/CPS webinar that was held on February 2, 2017.

4.1. The EU-US Funding and Collaboration Environment

4.1.1. EU and US Funding

The US R&I funding landscape is structurally very different to the EU landscape. EU-level funding is mostly centralized and is realized via major funding programmes such as *H2020*, the *ECSEL Joint Undertaking*, and *ERA-NET* (which focuses on pooling and coordinating funding of EU member states for EU joint calls) that provide EU-wide frameworks for R&I funding activities, covering all levels from fundamental over translational and applications-oriented research to knowledge transfer, innovation, and commercial deployment. In the US, the funding landscape is much more fragmented. Research and innovation is mostly funded by federal research programs that are set up by different federal agencies and that reflect directly the government's priorities and interests (3). Research funding is also available at the state level, but state funding normally focuses on specific local needs and is not usable for international collaboration.

Applications-oriented R&I funding is often provided directly by companies or industry-led associations to partnering research institutions in the form of grants, with a focus on short-term returns. Initiatives such as *H2020* or dedicated programs by US agencies usually focus on funding relatively large R&I projects, for which it usually takes months between the funding application and the start of work. On the other hand, direct funding by industry often focuses on a smaller scope and a relatively quick (e.g. within a few weeks) start of work after initial funding talks.

A major contact point in the federal US funding landscape in the areas of IT, computing, networking, and software is the *Networking and Information Technology Research and Development* (*NITRD*) Program, a multi-agency program that coordinates the funding of all federal agencies in this area. It has specific contact points that coordinate research across all agencies, such as CPS research and wireless communications incl. 5G.

The *National Science Foundation* (*NSF*) exclusively funds basic research and has a major CPS research program with more than 350 funded projects, plus funding for IoT research. The NSF has explored collaborations with the EU in the past, most successfully in the areas of environmental health and safety technology. In addition, there are several bilateral cooperation agreements with EU member states, such as the US-German IoT/CPS program, and interview partners have indicated significant interest in future programs for EU-US collaboration in the areas of IoT and CPS. The NSF will not cover EU costs, but it may cover costs for EU researchers visiting the US and vice versa. The NSF has already shown interest on collaborations on low-TRL research and is a good fit because it has a major initiative in CPS, in which energy aspects are of particular interest.

The NSF is a leader in supporting Big Data research efforts as well. These efforts are part of a larger portfolio of Data Science activities. NSF initiatives in Big Data and Data Science encompass research, cyber-infrastructure, education and training, and community building. In addition to funding the Big Data solicitation, and keeping with its focus on basic research, NSF is implementing a comprehensive, long-term strategy that includes new methods to derive knowledge from data; infrastructure to manage, curate, and serve data to communities; and new approaches to education and workforce development. “Big Data” is a new joint solicitation supported by the National Science Foundation (NSF) and the National Institutes of Health (NIH) that will advance the core scientific and technological means of managing, analysing, visualizing, and extracting useful information from large and diverse data sets. This will accelerate scientific discovery and lead to new fields of inquiry that would otherwise not be possible. NIH is particularly interested in imaging, molecular, cellular, electrophysiological, chemical, behavioural, epidemiological, clinical, and other data sets related to health and disease.

In the 5G area, the NSF coordinated the $400 million Advanced Wireless Research Initiative launched in 2016. As a first step, a Project Office for establishing the *Platforms for Advanced Wireless Research* (*PAWR*) has been created. The NSF has explored collaborations with the EU in the past, most successfully in the areas of health and safety technology. In addition, there are several bilateral cooperation agreements with EU member states, e.g. with Finland and Ireland. Potential collaboration mechanisms involving the NSF are e.g. joint workshops and mirrored calls.

The *National Institute of Standards and Technology* (*NIST*) is an important, more applications-oriented player in ICT funding (with a focus on supporting their own labs, not academia in general) and is active in a variety of technological areas and application sectors. In particular, it has a *Cyber Physical Systems Program* and a *CPS Public Working Group* that is currently developing a CPS framework (28), and its wireless networks division has a *5G & Beyond Program* and coordinates the *5G Millimeter Wave Channel Model Alliance* as well as working group developing the *Future Generation Communications R&D Roadmap*. NIST has already shown significant interest in the PICASSO work.

The parent organization of NIST, the *Department of Commerce* (*DoC*), also promotes other activities in the IoT/CPS domain. In 2016, the DoC has set as a policy priority to engage with the EU Digital Single Market initiative in the area of the free and open internet, and it also promotes activities in the telecommunications domain. The *National Telecommunications and Information Administration* (*NTIA*) of the DoC focuses on expanding broadband internet access and expanding the efficient use of spectrum, and it has published a “green paper” that reviews the current technological and policy landscape for the IoT and that highlights potential benefits and challenges, and possible roles for the federal government in fostering the advancement of IoT technologies in partnership with the private sector (29). In this paper, the NTIA promotes a globally connected, open, and interoperable IoT environment and recommends governmental support for US industry initiatives, greater collaboration between (private) standards organizations, the crafting of balanced policy and building coalitions, the enabling of infrastructure availability and access, and the promotion of technological advancement and market encouragement. The NTIA sees the role of government in the promotion of robust interagency coordination, public-private collaboration, and international engagement, while avoiding over-regulation that could stifle IoT innovation. International collaboration is encouraged across a range of activities and topics, including a consistent common policy approach for the IoT, cross-border data flows, privacy, and cyber-security, based on formal dialogues with top international partners on digital economy issues.

Other agencies that are potentially of interest as US partners for PICASSO collaboration mechanisms are the *Department of Energy* (*DoE*) that supports more applications-oriented research and development in areas such as clean energy, environmental cleanup, climate change, and other areas, has a strong track record in collaborations with European universities and research centers, and has shown interest in topics such as grid modernization and integrating renewables, the *Department of State* (*DoS*), the *Department of Homeland Security* (*DHS*), *Department of Defense* (*DoD*) agencies such as *DARPA*, the *Air Force Office of Scientific Research*, the *Army Research Office*, and the *Office of Naval Research*, and US foundations such as *Gordon and Betty Moore Foundation* and the *Blavatnik Family Foundation*. In addition, the *TAMS4CPS* project found that US national labs (such as Sandia) may be suitable contacts regarding funding for collaborations on more applications-oriented research.

The DoD is "placing a big bet on big data" investing approximately $250 million annually (with $60 million available for new research projects) across the military departments in a series of programs that will:

- Harness and utilize massive data in new ways and bring together sensing, perception and decision support to make truly autonomous systems that can maneuver and make decisions on their own.
- Improve situational awareness to help warfighters and analysts and provide increased support to operations. The Department is seeking a 100-fold increase in the ability of analysts to extract information from texts in any language, and a similar increase in the number of objects, activities, and events that an analyst can observe.

The *Defense Information Systems Agency* (*DISA*) offers a cloud-based set of solutions that enables the collection of large amounts of data from across the DoD Information Networks (DODIN) and provides the analytics and visualization tools to make sense of the data. The set of solutions is called *Cyber Situational Awareness Analytical Capabilities* (*CSAAC*) and is available on both *the Nonsecure Internet Protocol Router Network* (*NIPRNet*) and *Secret Internet Protocol Router Network* (*SIPRNet*). By using CSAAC, DoD network analysts and operators have a broader and more comprehensive view of DODIN activity than ever before. CSAAC enables informed decision making and enhances the overall security posture of DoD networks.

According to Deltek Principle Research Analyst Alex Rossino's new calculations, the *Defense Advanced Research Projects Agency*'s (*DARPA*'s) budget requests for big data research and development programs will grow by 39 percent in fiscal year 2016. In the past two years, DARPA's big data investments - which focus on advanced algorithms, analytics and data fusion, among other things - have spiked 69 percent, growing from just under $97 million in FY 2014 to more than $164 million in FY 2016. In addition, in 2012, DARPA initiated the 3-year $100M XDATA program to develop computational techniques and software tools for processing and analyzing massive amounts of mission-oriented information for Defence activities. Furthermore, to encourage future collaboration and innovation across the mathematic, computer science and visualization communities, DARPA open sourced the solutions for the general public.

The DoD and DARPA also support for example a spectrum collaboration challenge, where competitors are reimagining spectrum access strategies and developing new paradigms of collaborative decision-making where radio networks will autonomously collaborate and reason about how to share radio spectrum.

The *Department of Energy* will provide $25 million in funding to establish the *Scalable Data Management, Analysis and Visualization* (*SDAV*) Institute. Led by the Energy Department's Lawrence Berkeley National Laboratory, the SDAV Institute will bring together the expertise of six national laboratories and seven universities to develop new tools to help scientists manage and visualize data on the Department's supercomputers, which will further streamline the processes that lead to discoveries made by scientists using the Department's research facilities. The need for these new tools has grown as the simulations running on the Department's supercomputers have increased in size and complexity. Moreover, the DoE, with the support of partners and allies, has created the SEED Platform Collaborative to help put big data to work on one of the biggest problems in the global effort against the negative effects of climate change - the waste of energy in big buildings. The new *Standard Energy Efficiency Data* (*SEED*) Platform Collaborative creates a remarkable three-year partnership with regional and local governments to help them collect and manage data that tracks energy use in buildings, set aggressive goals for energy efficiency in them, and transform cities and regions into energy-saving leaders.

Other governmental agencies that support Big Data R&I are the *National Institutes of Health* (*NIH*) and the *US Geological Survey* (*USGS*). The NIH has announces that the world's largest set of data on human genetic variation – produced by the international 1000 Genomes Project – is now freely available on the *Amazon Web Services* (*AWS*) cloud. At 200 terabytes – the equivalent of 16 million file cabinets filled with text, or more than 30,000 standard DVDs – the current 1000 Genomes Project data set is a prime example of big data, where data sets become so massive that few researchers have the computing power to make best use of them. AWS is storing the 1000 Genomes Project as a publically available data set for free and researchers only will pay for the computing services that they use. The USGS has financed, through its John Wesley Powell Center for Analysis and Synthesis, a number of projects on Big Data in order to improve its understanding of issues such as species response to climate change, earthquake recurrence rates, and the next generation of ecological indicators. Funding was providing scientists a place and time for in-depth analysis, state-of-the-art computing capabilities, and collaborative tools invaluable for making sense of huge data sets.

Non-governmental actors play a major role in translational and application-oriented R&I, collaboration, and funding in the US and the EU, and are the main drivers in for applications-oriented ICT advancement. Non-governmental actors include multi-national companies (which have an inherently international point of view and are particularly dominant in the IoT sector), and industry-led associations and standardization bodies such as the *Industrial Internet Consortium* (*IIC*), the *International Council on Systems Engineering* (*INCOSE*), the *Smart Manufacturing Leadership Coalition* (*SMLC*), the *Object Management Group* (*OMG*), the *National Coalition for Advanced Manufacturing* (*NACFAM*), the *Conference of European Directors of Roads* (*CEDR*), and others. Our discussions with representatives from industry-led associations have shown that companies and associations are promising potential partners for future EU-US collaborations, also because they are less affected by governmental policy than federal agencies.

4.1.2. EU-US Collaboration

According to research conducted by the *BILAT USA 2.0* project, "nearly one-quarter of individual organisations' policy measures provide funds to other countries as long as the leading organisation is a U.S.-based university or other research institution. About 40% of the measures do not provide funding to non-U.S. institutions. The remaining 40% have specific pre-requisites for allowing receipt of U.S. funds by third countries".

In a recent study, the *DISCOVERY* project (26) analyzed the participation rate of US partners in H2020 projects and found that out of 52 running H2020 projects with US participation (with starting dates before June 2016), only three projects focus on IoT topics, and none on CPS topics, while the majority of projects are in the scope of personal healthcare (due to an existing bilateral agreement on health R&I between the EU and the US and thus eligibility of US organisations for H2020 funding). Two of the three IoT projects are within the scope of the *Future Internet Research & Experimentation* (*FIRE*) European initiative, which previously participated in a successful EU-US collaboration with its US counterpart, the NSF-funded *Global Environment for Networking Innovations* (*GENI*) program. The collaboration focused on the organization of joint thematic workshops and the exchange of personnel between the EU and the US.

Recently, EU-US collaborations have been set up based on coordinated calls and project twinning. To foster technological advances leading to the development of Next Generation Internet (NGI) and Advanced Wireless Networking (AWN) systems and technologies, the EU call "EU-US collaboration on NGI", which was published in the H2020 work programme 2018 – 2020, accepts project proposals that include twinning mechanisms (such as collaborative research initiatives or research exchange fellowships) with entities participating in projects funded by the US (via the program "US-EU Internet Core & Edge Technologies (ICE-T)" that is implemented by NSF) to exchange knowledge and experience and exploit synergies.

On the EU side, there are several examples where specific programmes opened project participation, and even funding in some cases, to US partners. The *Conference of European Directors of Roads* (*CEDR*), a consortium of public national road authorities or equivalents of European countries that focuses on applications-oriented research on road transportation topics, opened a recent call for projects to US participants[12], including the possibility of receiving funding from *CEDR*. The goal of this collaboration effort was to gain access to leading

[12] http://www.cedr.eu/download/other_public_files/research_programme/call_2016/CEDR-Call-2016-Information-Dec-2016.pdf

research experience from the US. The ERA-NET instrument that supports public-public partnerships for joint, transnational activities between EU member states (possibly with EU-level funding contributions) recently organized a workshop with the goal of making US and Brazilian funding agencies aware of the ERA-NET work and to discuss collaboration opportunities [13]. Follow-up activities are planned. In addition, selected ERA-NET programmes complement EU member state funding with external initiatives, including US-based funding. An example is *the Infrastructure Innovation Programme* (*Infravation*) for road infrastructure innovation[14].

Many multi-national companies (which by definition have subsidiaries in different countries that often collaborate) and industry-led associations have a strong track record of international collaboration and are open to participating in EU-US collaboration efforts. As an example, the *Industrial Internet Consortium* (*IIC*) is a global initiative that promotes the growth of the industrial IoT by bringing together partners from around the world, coordinating ecosystem initiatives, and bridging between regional initiatives (such as *Industrie 4.0* in Germany). Particular focus is currently placed on the 27 joint testbed initiatives[15], involving partners from many different countries. These joint testbeds provide realistic industrial environments for joint pre-competitive R&I projects so that new technologies, applications, products, services, and processes from different partners can be initiated, developed, and tested. As an example, the first of these testbeds, *Track&Trace*, was established appr. 2 years ago, is located in Germany, involves partners from the EU, the US, and India, and focuses on the development and testing of future smart, hand-held tools in manufacturing, maintenance, and industrial environments.

While collaboration initiatives between governmental agencies (such as the NSF and the EC) involve only few large organizations and are usually coordinated and set up internally, establishing collaborations between many different actors (such as government agencies on one side and industry-led associations, or even single large enterprises and SMEs on the other side) may require significant coordination and support activities. An example of a non-profit organization that specializes on this kind of match-making is the *Intelligent Manufacturing Systems* (*IMS*) Global Research and Business Innovation Program[16], which is partly funded by the EC. The program aims to integrate and connect US manufacturing industries and associations with EC programmes (where EC-foreign partners must provide their own funding). They focus on two services, direct matchmaking to set up R&I projects with partners from the member states, and thematic project clustering programmes for existing projects that provide collaboration support, such as the organization of workshops for international exchange.

4.2. Barriers

This section summarizes major barriers that must be overcome to implement successful EU-US collaborations. Most of these barriers have been identified in discussions within the IoT/CPS Expert Group and personal interviews done by the IoT/CPS Expert Group with external experts. Additions were provided by the Big Data and 5G Expert Groups.

4.2.1. Structural Differences in Funding Environments

As described in section 4.1, the US R&I funding landscape is structurally very different to the EU landscape along several dimensions.

First, EU-level funding builds on centralized framework programmes that do not have a counterpart in the fragmented US landscape. There are no overarching US or EU programmes currently that focus on closing the gap between centralized EU and decentralized US funding, although programs such as *Intelligent Manufacturing*

[13] https://www.b2match.eu/jpisgoglobal2016

[14] http://www.infravation.net

[15] http://www.iiconsortium.org/test-beds.htm

[16] http://www.ims.org

Systems (*IMS*, see previous section) provide bridging services for specific sectors. It seems unlikely that such overarching programmes are viable due differences in policy and due to the large administrative overhead that comes with the coordination of many different agencies and companies.

Second, different US funding agencies target specific technology readiness levels. The NSF focuses solely on basic research while other agencies (such as NIST, the DoE, national labs) focus on more applications-oriented translational research, and companies directly fund applications-oriented R&I. On the other hand, EU projects usually target several levels at the same time, and a single project may include basic research work, applications to realistic use cases, and even commercial deployment of novel technologies. Thus, high-level collaboration mechanisms, such as joint funding programmes or calls, are difficult to set up in a way that takes these differences into account. However, lower-level mechanisms that e.g. focus on the integration of US companies or industry-led associations for specific tasks within an EU project will be easier to accomplish.

Finally, there may be differences in the time spans between the application and the start of funding, and the funding cycles are not aligned between the EU and the US. EU projects are complex constructs that involve large consortia of partners from both, academia and industry, and it usually takes several months from the submission of an application to the start of funding. On the other hand, companies often have very specific R&I needs that can be achieved with relatively small effort, and they require a short-term return and a quick start of funding (e.g. within a few weeks) after application. However, EU projects are interesting for US companies for longer-term, more visionary R&I despite these timing differences, because these projects often run for several years, which provides planning security.

4.2.2. Administrative Overhead and Legal Barriers

International collaboration efforts always incur an administrative and bureaucratic overhead that can be a major barrier, as determined by the IoT/CPS expert group. There are many different potential mechanisms for EU-US collaboration, several of which have been successfully implemented before. The EU project *TAMS4CPS* has published proposals for such mechanisms (27), which can be separated into three different groups.

High-level, *top-down*, *heavyweight mechanisms* provide comprehensive frameworks for international collaboration. These include e.g. the **high-level multilateral agreements** between different countries (such as the 2016 Implementing Arrangement that was recently signed between the EU and the US[17]), large **thematic, targeted funding programmes** (such as the joint EC-NIH programme that supports EU-US collaboration in the health sector), and **joint calls** for R&I projects that pool funding all involved countries. High-level mechanisms usually require strong political support, and it often takes many years (estimated in interviews until 2020 when starting now) and a very large amount of work of all involved partners to set up such mechanisms.

Lower-level, *bottom-up*, *lightweight* mechanisms focus on specific collaboration aspects with smaller, targeted actions that can be set up relatively easily and quickly, and that occur a much smaller overhead than top-down programmes. These range from the **organization of joint workshops, conferences, and series of seminars** over support for the **mobility of researchers, staff exchange, fellowships to students, and training and education** and the trans-Atlantic provision of **access to research infrastructure, testbeds, and demonstrators** to (at the upper end in terms of complexity) relatively loose connections between calls for R&I projects, such as **coordinated calls** (for which both sides execute calls on a specific thematic topic that are temporally synchronized and that may support the involvement of external partners from both sides of the Atlantic, but where evaluation and funding is organized separately by each side) and **project twinning** (e.g. by implementing lightweight collaboration actions between existing R&I projects and consortia). The EC workprogrammes include

[17] http://ec.europa.eu/research/iscp/index.cfm?pg=usa

coordinated calls (such as the coordinated NGI initiative described above) as an instrument of a focused international strategy (25).

Finally, *collaboration support mechanisms* do not directly implement collaboration actions but provide support that facilitates the set-up of such actions. These include e.g. the facilitation of US participation in mainstream H2020 projects, the enhancement of framework conditions for trans-Atlantic collaboration, and the promotion of the visibility of EU/US programmes, as e.g. done in the *BILAT USA 4.0*, *PICASSO*, and *DISCOVERY* projects.

Our analysis and the interviews have conclusively shown that heavyweight mechanisms do currently not have a good chance of being successfully implemented in the IoT/CPS sector, particularly in the current political climate and if they require pooling of EU and US funding (see also below)[18]. The major reasons are the large overhead in the face of a lack of clearly visible benefits of such programmes and the fast evolution of the ICT field (and in particular of the IoT) that cannot be suitably reflected over the long time frames that are needed to set up high-level programmes.

Legal requirements are seen as major barriers for EU-US collaboration as well. In fact, many companies, for which the availability of external funding is often not an important requirement in joint R&I projects, see legal requirements as the major barrier for international collaboration. Companies are not interested in signing complex, restrictive legal documents. The initiatives that facilitate collaborations involving companies (such as the *Intelligent Manufacturing Systems* (*IMS*) program) restrict the legal requirements for partners by providing lightweight agreements and MoUs (memoranda of understanding).

It was noted by several interview partners that the need for US partners (in particular companies) to sign H2020 grant and consortium agreements has made it virtually impossible to involve commercial partners in H2020 aspects. However, this requirement has recently been removed under a new “Implementing Arrangement”[19] that was signed in October 2016 by the EU and the US. Under this new agreement, US organizations that do not receive any funding under H2020 are allowed to partake in research efforts and other relevant activities in the scope of EU projects without having to sign grant and consortium agreements, thus providing a new basis for EU-US R&I collaboration under Horizon 2020.

4.2.3. Lack of Clarity of the Benefits of EU-US Collaboration

The IoT/CPS expert group found that a major barrier to international collaboration is a lack of awareness and clarity about the benefits of EU-US collaboration activities for the participants, and a key requirement is the identification of these benefits and their communication to funding agencies, industry, and academia. Obviously, the more administrative and bureaucratic overhead a collaboration measure creates, the larger and more convincing the benefits must be. Questions that must be answered include e.g. “Is there a skill gap which can be complemented by collaboration?”, “Is there mutual economic benefit?”, “What will be missed if there is no collaboration?”, or “What are the common interests?” (see section 2).

Generally, collaborations within the research community are easier to justify than academic-commercial or pure commercial collaboration. The research community is inherently global and universal, and often significant advances in key areas are only possible in international collaboration efforts, e.g. by leveraging what EC academia can contribute, and vice versa. Major success stories of successful international collaboration efforts are e.g. CERN and the nuclear fusion reactor ITER. Another major benefit of EU-US research collaboration is that the

[18] Note that bilateral agreements between the US and a single EU member state are easier to implement than multilateral agreements between the US and the EU. Successful programs have e.g. been implemented between the US and Germany, the US and the UK, and the US and Ireland.

[19] http://ec.europa.eu/research/iscp/index.cfm?pg=usa

expansion of the horizons of scientific human capital (e.g. of students, graduates, post-docs) is a prerequisite for successful scientific research.

The identification of benefits for the inclusion of companies into collaboration efforts is more involved (although smaller companies are likely easier to identify for smaller companies than larger companies). There must be immediate incentives that justify the effort and the release of internal information and IP. Short-term benefits must be identified for concrete commercial and application scenarios within a restricted thematic area (such as additive manufacturing or specific scenarios involving the industrial IoT). Some general benefits for the involvement of companies in EU-US collaboration efforts are that in the globalized age, the merging of technologies from different parts of the world is an important competitive advantage that can lead to economic growth, that collaborations increase global visibility of a company, that different regions possess different strengths that can complement each other, and that collaboration may mitigate risks. For example, the US is strong in software and computing while the EU has unique strengths in smart production and cyber-physical systems development and deployment. In such a case, complementarity can create more than the sum of the parts when bringing different sectors together (provided the collaboration is not too close to commercial interests of the participants).

The advancement of international standardization and the sharing of infrastructure, testbeds, and demonstrators are other key benefits of EU-US collaboration (where again CERN and ITER are good examples of successful shared infrastructure). Infrastructure and testbeds are expensive to build, thus sharing will benefit both sides, and EU-US collaborations on standardization will set the standard for the rest of the world, in particular for the IoT sector in which all players are aware that trying to build a region-specific IoT is doomed to fail. Global efforts are seen as the only way forward.

In its recent survey (26), the *DISCOVERY* project asked respondents to identify the benefits that are most important for EU-US ICT collaboration. Gaining competitive advantages by an extended view of future challenges was identified as the most important benefit, followed by creating overseas relationships, sharing and gaining insights into research activities, and gaining international visibility.

4.2.4. Restrictions due to Intellectual Property Protection

Collaboration may be difficult on topics of **high near-term commercial importance**, i.e. innovation efforts that focus on products and services that may lead to large profitable businesses in the near term. Different regions are in competition, and industrial policy focuses on measures that reinforce own industry. This barrier is seen as important in all analyzed application sectors, and this is also a conclusion by the *BILAT USA 4.0* project that has found a lack of bilateral funding agreements between the EU and the US in areas with immediate economic outcomes. They state that “one reason for the lack of joint funding agreements may be that there are immediate economic outcomes where the US has a competitive advantage compared to the EU in the areas of technology levels, entrepreneurship, supporting start-ups, and venture capital.” (24).

It is thus arguably easier to collaborate on basic research than on applied research. An example is the *FET* (*Future and Emerging Technologies*) EC programme that focuses on basic research. Here, it is much easier to involve US partners (even including trans-Atlantic funding) than in other, more applications-oriented programmes, such as the ECSEL Joint Undertaking. One exception is the joint work on international standards and interoperability. While this is of commercial importance, it usually does not require companies to disclose information and technology that affects stand-out features of their products.

The Big Data expert group found that industrial competition between US and EU has a long tradition: It is widely accepted that EU and US are two competing regions, especially on technologically driven industries. Especially in the area of Big Data, Europe has been slow to adopt compared to the United States. More than half of worldwide revenue from big data is expected to come from the USA, and only one in twenty top big data companies is European (30). Thus, it can be very challenging for funding agencies and organisations from these regions, to collaboratively tackle research of high TRL (Technology Readiness Level) or applied research topics. However, tackling basic research subjects and topics can be an alternative.

The 5G expert group has identified this barrier as important for research topics that are already considered as study or work items in global standardization bodies, like 3GPP and IEEE. Hence, it will be easier to collaborate on fundamental research than on applied research.

4.2.5. Lack of Joint EU-US Funding Mechanisms and Policies

Generally, most of the EU funding will be used to fund EU companies and research institutes, and US funding will focus on the support of US organizations and companies. Thus, EU-US collaboration will always be a complement, or even an exception, to local and regional funding. This is not expected to change in the near future and is one of the reasons why high-level mechanisms such as joint calls or thematic, targeted funding programmes are difficult to implement (see above).

The Big Data expert group has also found that joint funding is a challenging task: As already known, US structures (both private and public) who are based in the US, have limited access to EU funding. US structures are eligible for participation in EU projects, but financial support is only available for calls where this is specified, e.g. the "Health" programme in general. In some cases, the financial support to the US partners is not possible even if the call targets collaboration with the USA. Potential US participants are therefore encouraged to contact research and innovation funding organisations in the US to seek support for their participation in Horizon 2020 (unless mirrored calls are established, see example of NGI call above, launched by the EC and by NSF). No jointly agreed mechanism is currently in place for co-funding Horizon 2020 research and innovation projects. On the other side, EU organisations willing to participate in US research programmes, face similar challenges, as it is almost impossible to receive funding from US agencies. Results from the newly signed EU-US agreement (signed in October 2016), which offers new opportunities for research cooperation, remain to be seen.

4.2.6. Export Control and Privacy Restrictions

Topics touching **export control issues**, **sensitive or classified data / information**, or **privacy issues** should be avoided. The EU and US national priorities, rules, and regulations are very different and will be difficult to harmonize, and generally legal and policy differences will be difficult to overcome in these areas. In particular export control issues have been identified in interviews as major blocking factors of international collaborations. Such issues must be dealt with appropriately before starting any collaboration actions.

The Big Data expert group found that data privacy is a complicated issue: The collection and manipulation of Big Data, as its proponents have been saying for several years now, can result in real-world benefits. However, it can also lead to big privacy problems (31). Both the EU and the US, have established a number of laws, policies and directives dictating the use of personal data by organisations and institutions willing to benefit from them. There are many differences between the laws regarding data privacy in the European Union and the United States, with the E.U. generally allowing more rights to the individual. With no single law providing comprehensive treatment to the issue, America takes a more ad-hoc approach to data protection, often relying on a combination of public regulation, private self-regulation, and legislation (32). Even after the US and the EU signed the EU-US Privacy Shield Framework (33), open issues remain, making it very challenging and complicated for organisations coming from these different regions to collaborate on research topics related to personal data.

4.2.7. Lack of Awareness and Knowledge

A lack of awareness and knowledge of EU and US actors of the other side is detrimental to collaboration. E.g., *BILAT USA 4.0* found that interested US actors may be unaware of how EU funding schemes operate (including misconceptions on how US partners can participate in H2020), and are not aware of the R&I priorities of the other side. In addition, it is often straightforward to connect to other initiatives within the US, but the EC landscape is fragmented, and the responsibilities may not be clear to US agencies.

This barrier is confirmed by an investigation of the *DISCOVERY* project (26) that identified as main barriers the lack of information on funding opportunities and programmes, the lack of knowledge about specific research areas and topics that are open to international cooperation, difficulties to understand the rules of participation in other countries, and a lack of partner search tools and methods.

Currently, several EC projects are working on solutions for these issues, including *PICASSO*, *TAMS4CPS*, *DISCOVERY*, and *BILAT USA 4.0.*

4.2.8. Lack of Interoperability and Standards

A **lack of interoperability and (device) standards** can be a barrier to collaboration. This is true for several of the application sectors, as described in section 2.5 and, in more detail, in (1). In addition, IoT/CPS systems were noted by our interview contacts as sometimes being highly regulated, which can stifle innovation.

4.3. Collaboration Opportunities

This section summarizes recommendations and opportunities for EU-US collaboration in the IoT and CPS sectors that were synthesized based on discussions with EG members, inputs from external experts from EU and US funding agencies, companies, industry-led associations, and academia, and an analysis of the results of projects that work towards EU-US collaboration development.

This section is at this stage speculative, since the success probability of future collaboration mechanisms that involve governmental actors will depend on the regulatory framework and conditions that will be enacted by the new US administration, and on the new directions that will be emphasized over the next months. Governmental actors are currently in a waiting mode, and it is seen as unlikely that any collaboration mechanisms can successfully be set up within the next months at the least. Mechanisms that focus on EU collaborations with non-governmental US actors may have a higher chance of success in the short term as commercial companies and associations are less affected by federal policy.

The following major conclusions can be drawn from the analyses and barriers described in the previous sections:

- While heavyweight collaboration measures are not considered to have a high probability of success in the IoT/CPS sector at this stage, **lightweight collaboration actions** are seen as being promising, in particular those with low complexity that are relatively easy to set up (e.g. joint workshops and staff exchange), and most of the contacted interview partners **indicated interest in setting up such mechanisms**. At the program level, coordinated calls and project twinning are seen as the only options with reasonable chances for success. However, since the set-up of these mechanisms takes significant effort and a long time, they should not be seen as primary mechanisms for EU-US collaboration in the near future.
- In addition to governmental agencies, **private companies and industry-led associations** were identified as promising partners for EU-US collaboration actions, because they are more interested in R&I results than funding (they often can provide their own funding or may even offer funding means to academic participants), are less affected by governmental policy than federal agencies, and are inherently internationally oriented, i.e. not focused on national boundaries. The set-up of collaboration actions involving many potential partners (e.g. enterprises and SMEs) will require **significant coordination, support, and facilitation efforts**. However, even if only governmental agencies are involved, the large disparity between the centralized EU and the decentralized US funding landscape may require facilitation support.

- EU-US collaboration projects on technological topics should focus on aspects that do not require companies to release IP that is too closely related to stand-out features of their products. Thus, collaboration actions might either focus on **pre-competitive R&I with a low-*TRL* (*Technology Readiness Level*)** or on other efforts that do not require access to sensitive company-internal IP, such as increasing **interoperability**, developing **international standards**, **joint demonstration**, **testbeds**, or **business model development**. In addition, there may be opportunities to collaborate on topics such as **energy, air, and water with a focus on developing parts of the world** (e.g., Africa, India, Latin America). Within this space, commercial opportunities may be more limited in the near term than in the US and in EU countries.
- One key requirement for the successful initiation of EU-US collaboration actions is **benefit assessment and promotion**. Collaboration actions will only be set up if the expected benefits are larger than the administrative overhead, and if these benefits are made very clear to all participants, such as funding agencies and private companies. The required benefits grow with the complexity of setting up and executing collaboration measures. While it is relatively easy to identify convincing benefits for research collaboration, the benefits of more applications- and innovation-oriented collaborations are less clear. In particular for private companies and industry-led associations, it is important to clearly identify the business and commercial benefits of collaboration actions, which is a non-trivial task that usually has to focus on a concrete technological or business scenario.
- Since private companies and industry-led associations are not interested in entering complex and restrictive legal relationships, measures that focus on improving framework conditions for EU-US collaboration should target the **reduction of legal requirements**. The new Implementing Arrangement that was signed in October 2016 by the EU and the US provides a good basis for the inclusion of US-based companies and associations.

Based on these conclusions and the other contents of the IoT/CPS section of the opportunity report, the following concrete collaboration opportunities are defined. Within PICASSO, these opportunities will be validated, refined, and promoted.

4.3.1. Roadmapping and Benefit Assessment

The first step in future EU-US collaboration measures in the areas of the IoT and cyber-physical systems should focus on roadmapping and the identification, assessment, and promotion of benefits.

The most desirable mechanism for this is the organization of **joint, thematic EU-US workshops** that are co-funded by the EC and suitable US partners (such as NSF, NIST, or industry associations like IIC and SMLC) – alternatively, there could be a “pair” of workshops in the topic, one funded by the EU and one by the US. Such workshops should focus on specific technological topics (i.e. a subset of the technology themes that are described in section 2) and should aim at fulfilling the following objectives:

- Bring together **a diverse group of experts from academia, industry, and government** to discuss specific joint collaboration opportunities.
- Identify **specific R&I topics and concrete technology and application scenarios** that can serve as the basis for targeted collaboration programmes and calls.
- **Synthesize a list of benefits** that can be used to justify the effort of collaboration actions to all involved parties, including researchers, industry and industry-led associations, and the EU and US funding providers (such as the EC, the NSF, or specific industrial consortia that are willing to open their funding to the outside).
- Generate **proposals for facilitation mechanisms** that can be used to identify suitable participation and funding structures within the diverse EU and US funding landscapes.

- Develop and disseminate **white papers** that concisely summarize the concrete scenarios, potential involved participants, benefits, and facilitation mechanisms and can serve as a basis for the definition of concrete R&I projects, calls, or coordinated work programmes.

The Trans-Atlantic Symposia on ICT Technology and Policy initiated by the PICASSO project are examples of such workshops: the first edition took place in Minneapolis, hosted by Technological Leadership Institute, University of Minnesota (June 2017), the second edition takes plane in Washington, DC in June 2018, hosted by Wilson Centre. On a longer time horizon, it is recommended to set up a dedicated CSA (Coordination and Support Action) that continues these roadmapping and benefit assessment activities, leading into concrete calls and project proposals (see below).

4.3.2. Facilitation and Industry-focused Research and Innovation

The set-up of collaboration actions involving many potential partners (e.g. enterprises, industry-led associations, and SMEs), and the elaboration of ways to link the centralized EU funding structure and the decentralized US structure will require significant coordination and facilitation effort that cannot be supplied by the funding agencies and the potential partners alone.

An **organization or network is needed that serves as a central contact point, coordinator, and facilitator** for the set-up and execution of **EU-US collaboration actions with many potential partners**, and for the integration **of non-governmental US entities into H2020 projects** (possibly inspired by the *Intelligent Manufacturing Systems* (*IMS*) Global Research and Business Innovation Program that provides similar support for the manufacturing sector). Such an organization must bring together entities from academia, industry, and the funding environment to define specific collaboration actions and topics, analyze and promote potential benefits of collaboration with/to these entities, identify suitable collaboration mechanisms and funding structures for a specific collaboration action, and support the partners in the execution of the collaboration action (e.g. by supporting the organization of collaboration workshops).

4.3.3. Lightweight Joint Research and Innovation

While top-down mechanisms such as joint targeted funding programmes and joint EU-US calls are currently seen as being too complex to set up, setting up **coordinated calls** between the EU and the US and **twinning of projects** are seen as interesting options for collaborative R&I.

It is recommended that **a joint, targeted EU-US collaboration work programme** - even on small scale - is set up based on the results of dedicated roadmapping and benefit analysis efforts (such as those described above). The closing dates of **coordinated calls** that are started against this work programme are synchronized between the EU and US, but proposals and projects are evaluated and funded separately (alternatively or additionally, the EC could open up calls for self-funded US partners). Calls should require project proposals to integrate mandatory (lightweight) collaboration items, such as short-term student, researcher, and staff exchanges between EU and US partners and regular joint workshops for knowledge and experience transfer. The involvement of **non-governmental partners**, such as enterprises, SMEs, and industry-led associations should be encouraged and supported by a facilitation mechanism or organization, as described in section 4.3.2. Collaborations of regional EU entities (e.g. cities) with regional US entities (e.g. with cities or US states) may be a viable option as well, albeit with limited impact.

Since a fruitful EU-US exchange of IoT, CPS, and application experts is seen as an important mechanism to advance the state of the art in these domains, a separate lightweight program should be set up that provides **fellowship and exchange funding** for students and researchers to work and study abroad, and that promotes knowledge transfer between the EU and the US by funding **joint workshops**, **conferences**, and **seminar series** on IoT and CPS topics. This program should provide a **twinning option** that allows to link these collaboration actions to running R&I projects.

Standards and interoperability define future markets and are often a basis for product development, and there is currently a strong push towards large-scale demonstrators and test beds not only in the US, but also in the EU (see e.g. (25)). The importance of **joint testbeds**, **demonstrators**, **and shared infrastructure** in particular for EU-US collaboration was pointed out by several interview partners from both, the EU and the US. Such test beds and demonstrators provide realistic, large-scale scenarios for the evaluation of all kinds of novel technologies (including those that are defined in section 3) and are thus an important prerequisite for the successful transfer of novel technology into practice. In addition, **(industry-driven) standardization activities** will gain importance over the next years, in particular in the quickly evolving IoT landscape, and international collaboration will be essential to ensure the interoperability and successful integration of future large-scale infrastructures.

Infrastructure sharing and the development and joint usage of **large-scale test beds and demonstrators** should become a focus area of EU-US collaborative research and innovation funding. The EU and US should launch **synchronized initatives** that (a) provide financial support and administrative assistance for researchers and industry representatives to do **joint experiments on existing infrastructure** in the IoT, CPS, and relevant application domains, and that (b) provide support for the set-up of **new testbeds and demonstrators** on high-priority technology topics. Successful international testbed and infrastructure initiatives should be used as an inspiration (such as the joint testbed initiative of the *Industrial Internet Consortium*), and **companies and industry-led associations should be encouraged to contribute to infrastructure sharing initiatives**.

5. Conclusions

This report outlines new **technology themes** and **collaboration opportunities and mechanisms** that have been identified as being promising for EU-US collaboration in the areas of IoT and CPS. The themes and opportunities were synthesized based on comprehensive analyses of the EU and US research and innovation priorities in the technology sectors and related application domains, the EU-US funding and collaboration landscape, and technological and policy barriers for EU-US collaboration. The contents of this report have been validated and refined extensively, e.g. based on in-depth discussions and online distribution and feedback actions with a large network of international experts, analytical research by the Expert Groups, PICASSO results, and other feedback collection mechanisms such as a public consultation on the PICASSO website.

The opportunity report provides a common view on priorities and future cooperation opportunities between the EU and the US and is a strong basis and guideline for concrete EU-US collaboration actions of the PICASSO project.

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